MAGNETIC SENSOR

CROSS-REFERENCE TO RELATED APPLICATIONS

The instant application is a continuation-in-part of U.S. Application Serial No. 09/649,416 filed on **August 26, 2000**, which claims the benefit of prior **U.S. Provisional Application Serial No. 60/151,220** filed on **August 26, 1999**, and which claims the benefit of prior **U.S. Provisional Application Serial No. 60/ 151,424** filed on **August 26, 1999**, all of which are incorporated herein by reference.

BRIEF DESCRIPTION OF THE DRAWINGS

In the accompanying drawings:

FIG. 1 illustrates a block diagram of a magnetic sensor;

FIG. 2a illustrates a side view of a magnetic circuit;

FIG. 2b illustrates a top view of a magnetic circuit;

FIG. 3 illustrates a block diagram of another embodiment of a magnetic sensor;

FIG. 4 illustrates a block diagram of several embodiments of a magnetic sensor incorporating first and second resonant circuits;

FIG. 5 illustrates a schematic diagram of a first coil incorporated in a magnetic sensor;

FIG. 6 illustrates a resonant behavior of a first resonant circuit;

FIG. 7 illustrates a schematic diagram of a second coil and associated capacitor incorporated in a magnetic sensor;

FIG. 8 illustrates a resonant behavior of a second resonant circuit;

FIG. 9 illustrates a process for determining a relative phase difference of two signals;

FIG. 10 illustrates a block diagram of a circuit for determining a relative phase difference of two signals;

FIG. 11 illustrates a block diagram of an embodiment of a magnetic sensor incorporating a first resonant circuit with distributed capacitance;

FIG. 12 illustrates an embodiment for detecting an opening angle of a door; and

FIG. 13 illustrates an embodiment of a magnetic sensor adapted to sense both sides of a vehicle.

DESCRIPTION OF EMBODIMENT(S)

Referring to **Fig. 1**, a **magnetic sensor 10** is incorporated in a **vehicle 12** shown schematically comprising a **door 14** that hinges with respect to a **first pillar 16** about a plurality of **hinges 18**. The **door 14** has a **latch/lock mechanism 20** that latches to a **striker**
5   **22** on a **second pillar 24**.

The **door 14** -- typically constructed with magnetically-permeable steel -- has intrinsic magnetic properties. For example, the **door 14** conducts magnetic flux, thereby enabling a permanent magnet to stick thereto. The **hinges 18** provide a relatively low reluctance path between the **door 14** and the **first pillar 16**. Moreover, the **latch/lock mechanism 20** and
10   the **striker 22**, when engaged, provide a relatively low reluctance path between the **door 14** and the **second pillar 24**. Elsewhere, the **door 14** is normally magnetically separated from the **body 26** of the **vehicle 12** by an associated **air gap 28**. Accordingly, the **hinges 18** and **striker 22** are magnetically connected by a **first magnetic path 30** along the **door 14**. Moreover, the **first 16** and **second 24 pillars** -- to which the **hinges 18** and **striker 22** are
15   respectively attached – are magnetically connected by a **second magnetic path 32** -- distinct from the **first magnetic path 30** – comprising the **body 26**, **structure 34**, or **powertrain 36** of the **vehicle 12**. Accordingly, the **door 14** is part of a **magnetic circuit 38** that is similar in nature to the core of a transformer, as illustrated in **Fig. 1**, wherein the **first 30** and **second 32 magnetic paths** together constitute a **closed magnetic path 40**.

20   The **magnetic circuit 38** further comprises at least one **first coil 42** operatively connected to at least one **first signal 44**, for example an oscillatory signal from an **oscillator 46**. The at least one **first coil 42** is located at an associated at least one **first location 48**, and responsive to the at least one **first signal 44** generates a magnetomotive force in the **magnetic circuit 38** so as to generate a **magnetic flux 49** therein. At least one **magnetic sensing element 50** is
25   operatively connected to the **magnetic circuit 38** at an associated at least one **second location 52** that is distinct from the at least one **first location 48**. The at least one **magnetic sensing element 50** senses the **magnetic flux 49**, which is responsive to the magnetomotive force from the at least one **first coil 42** and to the magnetic properties of the **magnetic circuit 38**.

30   For example, as illustrated in **Fig. 1**, in a first embodiment, the at least one **first coil 42** may comprise a plurality of **first coils 42.1, 42.2** at distinct **first locations 48.1, 48.2**, for example operatively coupled with uniform phasing to the **top 18.1** and **bottom 18.2 hinges**

that operatively couple the **door 14** to the "A" **pillar 16.1**. Furthermore, each **first coil 42.1, 42.2** may be placed around the associated **hinge 18.1, 18.2** or around one or more associated mounting bolts that attach the hinge to the **first pillar 16** or to the **door 14**; and the **magnetic sensing element 50** may comprise a **second coil 54** around the **latch/lock mechanism 20**, around the bolts that attach the **latch/lock mechanism 20** to the **door 14**, or around the **striker 22**; the associated **magnetic circuit 38** thereby forming a transformer with two primary windings comprising the **first coils 42.1, 42.2**; a secondary winding comprising the **second coil 54**; and a core comprising the **first pillar 16**, the **hinges 18.1, 18.2**, the **door 14**, the **second pillar 24**, the **air gap 28** around the **door 14**, and the remainder of the **body 26**, the **structure 34** and the **powertrain 36** of the **vehicle 12**. Stated in another way, the first embodiment comprises a transformer with three coils, two of them active and one of them passive.

The **first signal 44** comprises a sinusoidal voltage generated by an **oscillator 46** comprising a crystal stabilized (i.e. substantially drift-free) TTL square wave signal generated by a **microprocessor 56** and subsequently filtered by a band-pass filter. The signal from the **oscillator 46** is fed to a **coil driver 58** -- for example, through a buffer amplifier.

The oscillation frequency of the **oscillator 46** is selected, as a function of the expected noise sources, to enhance system performance. For example, a frequency different from that of AC power lines (e.g. **60 Hz**) could be chosen to avoid interference therefrom. Ultrasonic frequencies appear to be useful. The permeability of typical automotive steel is frequency dependent with a bandwidth of about **100 KHz**. The frequency range of the permeability of the associated **magnetic circuit 38** can likely be extended to **1 MHz** or higher by adding materials such as ferrite or mu-metal thereto.

The skin depth of the **magnetic flux 49** is responsive to frequency, so the depth of the **magnetic flux 49** in the **door 14** and the shape and reach of the associated proximity field can be varied by changing the oscillation frequency (or frequencies). The **oscillator 46** may be modulated either in amplitude, frequency, or by bursting.

Each at least one **first coil 42** is driven by an associated **coil driver 58** that provides sufficient power at an impedance compatible with the **first coil 42** so that the resulting **magnetic flux 49** is sufficiently strong to be detected by the at least one **magnetic sensing element 50**. The **coil driver 58** is also, for example, provided with short circuit protection and is operated so as to avoid saturation or clipping of the **first signal 44**. The **coil driver 58**

is designed to operate in an automotive environment, for example to operate over a associated range of possible battery voltages. The **first signal 44** from the **coil driver 58** may, for example, be either a voltage signal or a current signal.

The **coil driver 58** drives the **first coil 42** through a **sense/test circuit 60**. The **sense/test**
5   **circuit 60** senses either a current or voltage from the **first coil 42**, or a signal from a supplemental **sense coil 62**, or a combination of the three, to confirm or test the operation of the **first coil 42**. This also provides a continuous test of the integrity of the **door 14**. For example, a supplemental **sense coil 62** would directly sense the **magnetic flux 49** generated by the **first coil 42**. The **sense/test circuit 60** may also, for example, test the **first coil 42** for
10   an open or short so as to improve the reliability of the **magnetic sensor 10**, particularly when used to control the actuation of a **safety restraint actuator 64**, so as to prevent a false deployment or a failure to deploy when necessary. The integrity, or health, of the at least one **first coil 42** is, for example, tested every measurement cycle.

A plurality of **first coils 42** may be driven separately, as illustrated in **Fig. 1**, or connected
15   in series or parallel and driven by a common **coil driver 58**. The at least one **first coil 42** may, for example, be series resonated to increase the current flow therein, thereby increasing the amount of **magnetic flux 49** generated by the at least one **first coil 42**, and the amount of **magnetic flux 49** induced in the **magnetic circuit 38**. This also increases the magnitude and extent to the leakage field proximate to the **air gap(s) 28** of the **magnetic circuit 38**, thereby
20   extending the range of associated proximity sensing by the **magnetic sensor 10**. Increased **magnetic flux 49** in the **magnetic circuit 38** provides for a higher signal-to-noise ratio in the signal or signals received or detected by the **magnetic sensor 10**. When in series resonance, the inductive reactance of the **first coil 42** is canceled by an associated capacitive reactance, so that the resulting total impedance is purely resistive, so that a given operating voltage can
25   be accommodated, or an associated Q of the resonant circuit can be adjusted, either by adjusting the resistance of an associated series resistor or by adjusting the inherent resistance of the **first coil 42** (e.g. by adjusting either the size or length, or both, of the conductor thereof). The at least one **first coil 42** may be compensated for variations in temperature by incorporating an associated temperature sensor. For a coil mounted around a **hinge 18** on the
30   "A" **pillar 16.1**, the body metal would act as a heat sink to help maintain the temperature of the **first coil 42** near ambient temperature.

The **sense/test circuit 60** also provides a measure of the power delivered to the **first coil 42** so that the **magnetic flux 49** coupled to proximate metal objects can be estimated. For

example, a steel object such as another vehicle proximate to the **door 14** provides an alternate path for **magnetic flux 49** from the at least one **first coil 42**, which affects the **magnetic circuit 38** and the reluctance seen by the at least one **first coil 42**, thereby changing the load on the at least one **first coil 42**, which changes the power provided thereto by the **coil driver**

5   **58**. Generally, a portion of the **magnetic flux 49** generated by the at least one **first coil 42** is coupled within the **magnetic circuit 38**, and a portion bypasses the **magnetic circuit 38**, whether via an alternate magnetic path or by radiation. The portion of **magnetic flux 49** that bypasses the **magnetic circuit 38** increases the load upon the **coil driver 58**, which increase is sensed by a **bypass power processor 66** using measurements from the **sense/test circuit**

10   **60** of the voltage across and the current through the at least one **first coil 42**. For a plurality of **first coils 42**, the **bypass power processor 66** can provide a measure of direction to a proximate magnetic-field-affecting object from the separate measurements of the associated separate **sense/test circuits 60.1** and **60.2**, particularly from a measure of the difference in currents flowing to the separate **first coils 42.1** and **42.2** for a given common drive voltage.

15   The at least one **magnetic sensing element 50** is responsive to the **magnetic flux 49** at the **second location 52**, including both a first portion of **magnetic flux 49** that is conducted through the **door 14**, and a second portion of **magnetic flux 49**, i.e. leakage flux, that bypasses at least a portion of the **door 14** -- for example as a result of an object, such as another vehicle proximate to the **door 14**, that couples **magnetic flux 49** from the at least one

20   **first coil 42** to the at least one **magnetic sensing element 50**.

An output from the at least one **magnetic sensing element 50** is operatively connected to a **preamplifier/test circuit 68** which, for example, buffers the **magnetic sensing element 50** from loading by the subsequent circuitry and provides a relatively low impedance output so as to reduce noise. The **preamplifier/test circuit 68** also amplifies the signal from the at least

25   one **magnetic sensing element 50** to a level sufficiently high to permit appropriate signal processing and demodulation before subsequent analog-to-digital conversion for processing by the **microprocessor 56**. The **microprocessor 56** gathers data, monitors system health and integrity, and determines whether or not to actuate the **safety restraint actuator 64**.

The **preamplifier/test circuit 68** also monitors the integrity of the **magnetic sensing**

30   **element 50**, for example by comparing the signal therefrom with "expected" levels and expected wave shapes (e.g. a sinusoidal shape). This provides a continuous test of the integrity of the **magnetic sensing element 50** and the magnetic transfer function property of the **door 14**. The **preamplifier/test circuit 68** may also, for example, test the at least one

magnetic sensing element 50, for example a second coil 54, for an open or short so as to improve the reliability of the magnetic sensor 10, particularly when used to control the actuation of a safety restraint actuator 64, so as to prevent a false deployment or a failure to deploy when necessary. The integrity, or health, of the at least one magnetic sensing
5   element 50 is tested every measurement cycle.

The magnetic sensing element 50 senses from the magnetic flux 49 proximate thereto a sinusoidal carrier that is modulated responsive to the reluctance of the magnetic circuit 38. This signal from the magnetic sensing element 50 is amplified by the preamplifier/test circuit 68, and a synchronous demodulator 70 operatively connected thereto extracts the
10   modulation signal from the sinusoidal carrier, which modulation signal contains a bent metal signal component 72 and a proximity signal component 74. The bent metal signal component 72 is responsive to the magnetic flux 49 conducted through the metal of the door 14. The proximity signal component 74 is responsive to the leakage magnetic flux 49 that is coupled between the at least one first coil 42 and the magnetic sensing element 50
15   along a path that bypasses the metal of the door 14. The difference in the relative strengths of the bent metal signal component 72 and a proximity signal component 74 is dependent upon the difference in permeances of the associated magnetic flux paths.

A bent metal processor 76 DC couples -- with, for example, unity gain -- the bent metal signal component 72 to the microprocessor 56 through an A/D converter 78.1. The bent
20   metal signal component 72 is responsive to the time rate of change of magnetic flux 49 in the door 14. Relatively slow signals of relatively low amplitude correspond to non-deployment events for which a safety restraint actuator 64 should not be deployed, for example a low speed impact of the door 14 by a shopping cart. Relatively fast signals of relatively large amplitude correspond to deployment events for which a safety restraint
25   actuator 64 should be deployed, for example an impact of the door 14 by a pole or barrier (e.g. an FMVSS-214 condition). During a pole crash, the steel of the door 14 becomes magnetically shorted to the adjacent body, thereby magnetically shorting the flux path -- as a result of either the magnetic influence of a proximate magnetic object (e.g. a steel pole), or by the physical affect of the impact on the associated magnetic circuit 38 -- which significantly
30   reduces the magnetic flux 49 sensed by a magnetic sensing element 50 at the striker 22. The magnetic sensing element 50 is responsive to those changes to the magnetic circuit 38 which either increase or decrease the associated magnetic flux 49 sensed thereby.

The **proximity processor 80** amplifies the **proximity signal component 74** from the **synchronous demodulator 70** by some gain factor based on coil geometry and vehicle structure, and DC couples the amplified signal through an **A/D converter 78.2**. The **proximity signal component 74** is responsive to the time rate of change of **magnetic flux 49** that bypasses **door 14**. Notwithstanding a greater susceptibility to noise in comparison with the **bent metal signal component 72**, the **proximity signal component 74** enables the detection of metallic (particularly ferromagnetic) objects that are approaching the **door 14**, for example a vehicle approaching at high speed or a vehicle in an adjacent lane of traffic. Another vehicle approaching the **door 14** on a collision course therewith is indicated by a relatively fast signal, for which a **safety restraint actuator 64** would be deployed upon impact if followed by a corresponding **bent metal signal component 72**.

Accordingly, if the rate of change of the **proximity signal component 74** is greater than a first threshold, then the **safety restraint actuator 64** is deployed when the **bent metal signal component 72** exceeds a second threshold and the rate of change thereof exceeds a third threshold. Otherwise, if no bent metal signature follows, for example if the **proximity signal component 74** had resulted from a passing vehicle, then the system stands down.

The above described **magnetic sensor 10** can be embodied in various ways. The particular circuitry, whether analog, digital or optical is not considered to be limiting and can be designed by one of ordinary skill in the art in accordance with the teachings herein. For example, where used, an oscillator, amplifier, logic element, modulator, demodulator, A/D converter can be of any known type, for example using transistors, for example field effect or bipolar, or other discrete components; integrated circuits; operational amplifiers, or logic circuits, or custom integrated circuits. Moreover, where used, a microprocessor can be any computing device.

In accordance with the theory of magnetic circuits and transformers, magnetic lines of flux always close on themselves and preferably follow a path of least magnetic resistance, for example so as to follow the path of ferromagnetic materials, such as steel or ferrite materials. Moreover, changes in area or permeability along the magnetic circuit cause a leakage of **magnetic flux 49** proximate thereto, which leakage is also known as fringing. A **magnetic circuit 38** is characterized by a reluctance $\mathcal{R}$, wherein the amount of magnetic flux ϕ in a magnetic circuit for a given magnetomotive force **F** is given by $\phi = F/\mathcal{R}$. The reluctance $\mathcal{R}$ of a series magnetic circuit is given by the sum of the respective reluctances of the respective

elements in series. The reluctance of an air gap is significantly greater than that of a ferromagnetic material, and as a result, the magnetic flux leaks into the space surrounding the air gap, forming a leakage field. A ferromagnetic object entering the leakage field provides an alternate path for the magnetic flux, thereby bypassing the air gap and affecting the

5   reluctance of the **magnetic circuit 38**. Stated in another way, the leakage flux field changes shape so that the ferromagnetic object becomes part of the **magnetic circuit 38**.

As illustrated in **Fig. 1**, a **door 14** can be modeled as an element of a closed **magnetic circuit 38** that is similar to a transformer core. The fore and aft ends of the **door 14** are magnetically connected in series with the remainder of the **magnetic circuit 38** by the **hinges**

10   **18** and the coupling of the **latch/lock mechanism 20** to the **striker 22**. The remainder of the **door 14** is magnetically insulated from remainder of the **magnetic circuit 38** by an **air gap 28** that otherwise surrounds the **door 14**.

A **first coil 42** has a self-inductance which has one value when the first coil is in free space, and another when the coil is operatively connected to a **magnetic circuit 38**, for

15   example by wrapping the **first coil 42** around a portion of the **magnetic circuit 38**. In the latter case, the self inductance of the **first coil 42** is dependent upon the magnetic properties of the **magnetic circuit 38**. Moreover, the magnetic properties of the **magnetic circuit 38** are altered if the **magnetic circuit 38** is physically deformed, or if ferromagnetic elements are brought in proximity with the **magnetic circuit 38**, particularly in proximity with the

20   leakage fields thereof. Accordingly, a deformation of the **door 14** or the approach of another vehicle to the **door 14** are both examples of perturbations to the magnetic properties of the **magnetic circuit 38**, both of which can be detected by either a change in inductance of the **first coil 42**, or by a change in the magnetic coupling between a **first coil 42** at a **first location 48** and a **magnetic sensing element 50** for sensing the **magnetic flux 49** in the

25   **magnetic circuit 38** at a **second location 52** distinct from the **first location 48**.

In operation, the at least one **first signal 44** operatively coupled to the associated at least one **first coil 42** by the associated at least one **coil driver 58** causes a current flow in the at least one **first coil 42** which generates a **magnetic flux 49** therein, which in turn generates a **magnetic flux 49** in the **magnetic circuit 38** to which the at least one **first coil 42** is coupled.

30   The **magnetic flux 49** is conducted by the **door 14**, which is a part of the **magnetic circuit 38**. The at least one **first signal 44** comprising an oscillating signal, for example a sinusoidal voltage or current excitation, is applied to at least one **first coil 42** operatively coupled to a **hinge 18** of a **door 14**. Referring to **Figs. 2a** and **2b**, the at least one **first coil 42** converts the

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at least one **first signal 44** into **magnetic flux 49**, which is then induced in the **magnetic circuit 38** by virtue of the at least one **first coil 42**. The **magnetic flux 49** comprises a plurality of **magnetic flux lines 84**, some of which may leak out beyond the physical boundary of the **magnetic circuit 38**, particularly at locations proximate to **air gaps 28** in the

5   **magnetic circuit 38**. The **magnetic flux lines 84** follow steel and other ferromagnetic elements of the **door 14** that attract **magnetic flux 49** therein in relation to the permeance thereof in comparison with the substantially lower permeance of the surrounding air.

The at least one **first signal 44** from the **oscillator 46** is amplified by the associated at least one **coil driver 58** and operatively coupled to the at least one **first coil 42** through an

10   associated **sense/test circuit 60**. The at least one **first coil 42** generates a **magnetic flux 49** in the **magnetic circuit 38**, particularly the **door 14**, and at least a portion of the **magnetic flux 49** is sensed by the **magnetic sensing element 50**, for example by a **second coil 54** wrapped around the **striker 22**.

The **magnetic flux 49** travels through the **magnetic circuit 38**, particularly the

15   ferromagnetic portions thereof including those of the portions of the **vehicle 12**, such as the **door 14**, that are monitored by the **magnetic sensor 10**. A **first portion 86** of the **magnetic flux 49**, known herein as the **bent metal flux component 86**, passes through the ferromagnetic elements of the **magnetic circuit 38** and is sensed by the **magnetic sensing element 50**, which provides a **first signal component 72** known herein as a **bent metal**

20   **signal component 72** that is responsive thereto, or in other words, that is responsive to changes of the magnetic characteristics of the **magnetic circuit 38**. The **magnetic flux 49** seeks to travel inside the steel structure of the **door 14**. More **magnetic flux 49** automatically enters those parts of the steel that are thicker, which would likely correspond to those elements of the door structure that add strength to the **door 14**. Where the steel is

25   thinner, the magnetic flux density is correspondingly reduced. Stated in another way, the **magnetic flux 49** travels in ratiometric proportion with the cross-sectional area of the steel. The **magnetic flux 49** is generally not present in the plastic parts other than as a result of leakage elsewhere in the **magnetic circuit 38**, however, for a steel **door 14**, these parts are generally not structural. Accordingly, the **magnetic sensor 10** generates **magnetic flux 49**

30   that passes through the structural elements of the **door 14**, and is responsive to mechanical changes to these structural elements to a degree that those mechanical changes influence the **magnetic flux 49**.

A **second portion 88** of the **magnetic flux 49**, known herein as the **proximity flux component 88**, extends outside the physical extent of the **magnetic circuit 38** and is sensed by the **magnetic sensing element 50**, which provides a **second signal component 74** known herein as a **proximity signal component 74** that is responsive thereto, or in other words, that is responsive to changes of the magnetic characteristics of a region proximate to the **magnetic circuit 38**.

Changes to the size, shape, position, construction integrity, spot-weld quantity and integrity, material correctness, and assembly alignment of the **door 14**; or to the magnetic environment proximate to the **door 14**, for example, by the presence of a ferromagnetic object such as **another vehicle 90**; affect the **magnetic circuit 38**, and thereby affect **magnetic flux 49** sensed by the **magnetic sensing element 50**.

The **door 14**, or another part of the **magnetic circuit 38** subject to surveillance, may be supplemented or modified by adding or relocating steel or other highly permeable material in the **door 14** to as to modify the strength and/or shape of the respective **first 86** and **second 88 portions** of the **magnetic flux 49**, thereby enhancing the associated **magnetic circuit 38** so as to improve the respective **bent metal 72** and/or **proximity 74 signal components**. This may further enable a reduction in power to at least one **coil driver 58**, thereby reducing associated radiated power from the at least one **first coil 42**. Moreover, this may enable a reduction in gain of the associated **preamplifier/test circuit 68**, which improves the associated signal-to-noise ratio. The **magnetic flux 49** generally follows a path of least reluctance, which typically would correspond to sections of greatest amounts of magnetically permeable material. For a **door 14** constructed of steel, this path would then correspond to one or more sections of the **door 14** that contribute substantially to the strength of the **door 14**. Accordingly, the **magnetic circuit 38** can be optimized with respect to magnetic performance, strength and cost by this supplementation or modification of the associated magnetically permeable material.

For example, the **magnetic circuit 38** can be modified or augmented in various ways, including but not limited to the following, many of which provide for increasing the ratio of magnetic flux density per unit drive current and thereby increase the magnetic efficiency of the **magnetic circuit 38**:

1. Mu-metal, ferrite or some other magnetic conductor can be added to the **door 14**, for example to a plastic **door 14**, e.g. by coating the inside of the door 14 with a ferrite

paint or coating to increase the permeability thereof, to augment or re-tune the door's natural magnetic characteristic;

2. Holes may be added to the **door 14** or modified, thus shifting the magnetic conduction;

3. A supplemental ferrite or mu-metal flexible linkage may be added between the "A" **pillar 16.1** and the **door 14** for generating the **magnetic flux 49**, instead of the **hinges 18**;

4. Ferrite, an amorphous metal (e.g. METGLAS®), or mu-metal may be placed in the **striker 22** and **second coil 54**, or generally added to or used as the core of either the **first 42** or **second 54 coil 42** to enhance the **magnetic flux 49** therein, or to provide for operating at a lower current level for the same amount of **magnetic flux 49**;

5. A permanent magnet may be added to the **door 14** to augment or re-tune the intrinsic permanent magnetic characteristic signal of the **magnetic circuit 38**;

6. The magnetic structure of the **door 14** can be changed, for example by using a thinner metal skin, a plastic door skin, or ferrite rods to change the magnetic gain, so as to enhance proximity sensing for enhanced system safing responsive to the **proximity flux component 88**;

7. The hinge or striker shape, size, or material can be changed to improve their associated magnetic characteristics; and

8. The door side-guardrail assembly and construction, the hinge assembly, or the latch/lock mechanism/striker assembly can be changed to enhance system performance and sensitivity.

In addition to the herein described use in detecting a crash or an impending crash, the **magnetic sensor 10** can also be used to monitor the structural integrity of structural elements of the **magnetic circuit 38**, particularly the structural integrity of the **door 14**, for example as a post manufacturing inspection of a **door 14** either mounted to a **vehicle 12**, or separate therefrom in a magnetic circuit of an associated test apparatus. For example, a missing structural element, such as guard rail, or poor spot welds, would likely affect the reluctance of the **door 14** and if so, could be detected prior to assembly. Stated another way, a steel **door 14** that does not conduct **magnetic flux 49** well would not likely have sufficient side-impact strength. Accordingly, the **door 14** can be tested for proper magnetic integrity, which can be predictive of the performance of the **magnetic sensor 10**, and indicative of the ability of the **door 14** to withstand impact and thereby protect an occupant therefrom.

The **magnetic sensing element 50** is responsive to a superposition of the **first 86** and **second 88 portions** of **magnetic flux 49**, and converts the composite of both portions to a voltage that is amplified by the **preamplifier/test circuit 68**, wherein the relative strengths of the associated **bent metal 72 and proximity 74 signal components** is in proportion to the associated relative strengths of the **first 86** and **second 88 portions** of **magnetic flux 49**. The **magnetic sensing element 50** may be Faraday shielded to reduce noise, wherein a Faraday shield would shield the **magnetic sensing element 50**, e.g. **second coil 54**, from stray electric fields so as to prevent or reduce noise in the signal therefrom. For a **magnetic sensing element 50** comprising a **second coil 54**, for example around the **striker 22**, the **second coil 54** may be also be parallel resonated to match the associated carrier frequency of the at least one **first signal 44** so as to improve the associated signal-to-noise ratio. Parallel resonance of the **second coil 54** provides for increasing the strength of the signal therefrom, and for increasing the sensitivity thereof to variations in the **magnetic flux 49** in the **magnetic circuit 38**. Experiments have shown that locating the **second coil 54** proximate to the **end wall 92** of the **door 14** enhances the awareness of the **proximity flux component 88** of the **magnetic flux 49**. This suggests that the **latch/lock mechanism 20** -- a localized thickening of the door metal -- may act be as a magnetic lens to magnify the effect of the **proximity flux component 88** at the **second coil 54**. The **air gap 28** helps to create the **proximity flux component 88**, and the region of greatest sensitivity by the **proximity flux component 88** to approaching objects is proximate to the **air gap 28**. Impacts to the **door 14** tend to modulate the **air gap 28**, causing significant changes to the associated **magnetic flux lines 84**, thereby causing the **magnetic sensing element 50** to generate an associated signal of significant magnitude. The signal responsive to the modulated **air gap 28** provides a measure of instantaneous recoil velocity of the **door 14**, which may be used to detect door bounce events for which an associated **safety restraint actuator 64** is typically not deployed. The **magnetic sensor 10** can be responsive to movement of a latched **door 14**,

More particularly, the **door 14** acts as a rigid body at the beginning of a collision and is pushed inwards towards the body of the **vehicle 12** against the compliance of the weatherseal surrounding the **door 14**, thereby exhibiting elastic behavior. The **magnetic flux 49** sensed by the **magnetic sensing element 50** changes responsive to the movement of the **door 14**, thereby enabling the lateral position and velocity of the **door 14** to be measured from that change.

If the momentum of the impact is less than a threshold, for example for small objects or low impact velocities, the **door 14** will then bottom out within a range of elastic behavior and rebound, thereby reversing the above described change to the **magnetic flux 49** which is indicated by a shift in polarity of the signal from the **magnetic sensing element 50.**

5 Accordingly, the detection of such a rebound event is indicative of an impact for which the **safety restraint actuator 64** would not be necessary. Otherwise, if the momentum of the impact is greater than a threshold, then the **door 14** becomes plastically deformed, resulting in a significant change to the **bent metal signal component 72**, which can be indicative of a need to subsequently deploy the **safety restraint actuator 64.** Accordingly, if after an initial

10 movement of the **door 14** is detected, either the **door 14** fails to rebound and/or a significant **bent metal signal component 72** is detected, then the impact might be considered to be sufficiently severe to warrant the deployment of the **safety restraint actuator 64.** Moreover, the initial velocity of the **door 14** can be used as a predictor or indicator of impact severity.

A ferromagnetic **door 14** is characterized by an associated natural permanent magnetic

15 field which acts to generate a static **magnetic flux 49** within the **magnetic circuit 38** responsive to the reluctance of the **magnetic circuit 38**, changes to which as a result of door motion are sensed by the **magnetic sensing element 50.** This response – effectively an AC transformer transfer component -- is superimposed upon the response to the at least one **first signal 44**, and can provide an independent measure of door motion and impact velocity.

20 Experiments have shown that responsive to an FMVSS-214 impact the **door 14** can rotate about its centerline causing – at the beginning of the impact -- an increase in the **air gap 28** between the **door 14** and the vehicle body at the top of the **door 14.** By comparison, experiments have shown that a pole-type impact causes a corresponding reduction in the **air gap 28.** Accordingly, the behavior of the **air gap 28** responsive to a crash can be used to

25 identify the type of crash. Accordingly both the type and severity of the crash can be detected by the **magnetic sensor 10.** Commencing with an impact, the **door 14** is generally moves readily responsive to the crash until the **latch/lock mechanism 20** bottoms out against the associated **striker 22.** Accordingly for a striking object that is relatively massive in comparison with the **door 14**, the velocity of impact can be measured by the **magnetic**

30 **sensor 10** from the motion of the **door 14** prior to this "bottoming out" thereof. After the **door 14** "bottoms out" against the vehicle body, the impact causes bending or deformation of the **door 14**, causing further changes to the **magnetic circuit 38** that are sensed by the

magnetic sensor 10, providing further information about the intensity and duration of the crash.

Another vehicle 90 proximate to the at least one first coil 42 attracts magnetic flux 49, thereby causing a third portion 94 of the magnetic flux 49 generated by the at least one first coil 42 to bypass the magnetic sensing element 50. Moreover, if the door 14 becomes dented or deformed, the distribution and/or strength of the magnetic flux 49 in the door 14 changes, which change is sensed either by the magnetic sensing element 50 or by a change in the load upon the at least one first signal 44 by the at least one first coil 42. Accordingly, substantially the entire door 14 acts a sensing element of the magnetic sensor 10, wherein the effect of changes to the magnetic characteristics thereof on the number and distribution of the magnetic flux lines 84 propagates at the speed of light from the location of the disturbance to either the at least one first coil 42 or the magnetic sensing element 50. Moreover, by placing the at least one first coil 42 on at least one hinge 18, and the second coil 54 on the striker 22, the door 14 becomes a sensing element without actually running any wires or signal cables into the door 14. The magnetic sensor 10 using the door 14 as a sensing element in a proximity sensing mode can be used to either monitor a blind spot of the vehicle 12 or to monitor traffic in an adjacent lane. The extent of coverage by the proximity mode can be increased by increasing the strength of the associated magnetic flux 49, e.g. by increasing the current supplied to the first coil 42, or by adapting the associated magnetic circuit 38 to increase the associated proximity flux component 88.

With substantially the entire door 14 as a sensor, the magnetic sensor 10 can sense incoming objects approximately of door dimension. Car bumpers and roadside poles similar to the door dimension, for which a safety restraint actuator 64 would be required in a crash, will generally be visible whereas basketball and other small objects, for which a safety restraint actuator 64 would not be required, would be less visible. A shopping cart loaded with groceries would also be visible to the magnetic sensor 10, however the decision of whether or not to deploy a safety restraint actuator 64 would be based upon more factors than just the visibility of a particular object. The magnetic sensor 10 is not responsive to impacts such as impacts to the undercarriage, for example from a rock, that do not affect the magnetic circuit 38, but which might otherwise affect an acceleration based crash sensor.

Accordingly, the magnetic sensor 10 is responsive to various to various physical effects upon the magnetic circuit 38, including but not limited to the following:

1) Changes to the **air gap 28** of the magnetic circuit affecting the **bent metal signal component 72**.

2) Changes in the shape and density of the **proximity flux component 88** proximate to the **air gap 28** surrounding the **door 14**, including the front edge of the **door 14** and front fender, the rear edge of **door 14** and rear fender (or the rear **door 14** of a four (4) door vehicle), the bottom of the **door 14** to floor board, and, to a lesser extent, the top of the **door 14** or window frame to the roof. The **bent metal signal component 72** is responsive to deformations of the **door 14** or adjacent body components that close, or short, the **air gap 28**.

3) The **door 14**, particularly the skin thereof, has a natural resonant frequency that can be excited by the at least one **first coil 42** if driven at that frequency the at least one **first signal 44**. An impact to the **door 14** induces vibrations therein associated with the resonant frequency thereof, and with associated overtones. At this resonant frequency, if the vibrating elements of the **door 14** become constrained as by contact with an impacting object, this causes a dampening of the resonance which increases the eddy current losses in the **magnetic circuit 38**, which can be measured by the **bypass power processor 66** from the power supplied to the at least one **first coil 42**. Furthermore, the impacting object can influence the associated resonances, so that the nature of the resonances measured by the **magnetic sensor 10** provides associated information about the nature of the impact – e.g. severity -- or the nature of the impacting object. Stated in another way, the **door 14** has a natural resonant behavior, but exhibits a forced response to the impact thereof by an impacting object because of the continued interaction of the impacting object with the **door 14**.

4) The structural elements of the **door 14** typically provide a path of least reluctance for the associated **magnetic flux 49**, and mechanical stresses therein can alter the reluctance thereof, so that changes to the **magnetic flux 49** can be related to the level of forces applied to the **door 14** and to the structural elements thereof, which force levels can be related to the momentum or velocity of the impacting object. Accordingly, the measurements of the **magnetic flux 49** provides a measure of threat to the **door 14**.

The **bent metal 72** and **proximity 74 signal components** in the composite signal from the **magnetic sensing element 50** are demodulated by the **synchronous demodulator 70** and amplified by different respective gains of the associated **bent metal 76** and **proximity 80**

processors, wherein the respective gains are for example in proportion to the relative permeance of the materials associated with the respective magnetic flux components. The **bent metal 72** and **proximity 74 signal components** differ with respect to signal magnitude, and without further differentiation, only one of the two components would be useful at a given time. Prior to impact, the **proximity signal component 74** provides information about a proximate object. However, after the occurrence of an impact, the **proximity signal component 74** becomes relatively small, if not insubstantial, in comparison with the corresponding **bent metal signal component 72**. For example, the **proximity signal component 74** might have a magnitude of **0.2** volts, which is about twenty five times smaller than the corresponding **bent metal signal component 72** after impact, which might have a magnitude of **5.0** volts. For example, when the **bent metal signal component 72** is of sufficient magnitude to indicate a physical disturbance of the **magnetic circuit 38**, then the **proximity signal component 74** would be saturated. Otherwise, the **bent metal signal component 72** would be of negligible magnitude and the **proximity signal component 74** would be useful for detecting objects proximate to the **door 14**. This mutual exclusive utility of the respective signal components is consistent with the sequence of a crash, in that an impacting object becomes proximate to the **vehicle 12** before impacting the **door 14**; and after the impact has occurred as indicated by the **bent metal signal component 72**, there would likely be little need to continue to detect the **proximity signal component 74**.

Given the **bent metal 72** and **proximity 74 signal components**, the **microprocessor 56** can monitor the total magnetic health of the **door 14** and be aware of relatively large metal objects in proximity thereto. An example of one algorithm using this information to control a **safety restraint actuator 64** would be to monitor the **proximity signal component 74** to detect a relatively rapid approach of a relatively large metal object. When the **proximity signal component 74** becomes saturated, indicating a likely perturbation to the physical **magnetic circuit 38**, then if the **bent metal signal component 72** indicates a sufficiently large change, then it is assumed that a potentially injurious impact has occurred and the **safety restraint actuator 64** would be actuated. Otherwise, if the **proximity signal component 74** returns to a quiescent state without the occurrence of a significant **bent metal signal component 72**, then it is assumed that the **door 14** has not been impacted, but instead, for example, another vehicle has passed by the **door 14**, and the **safety restraint actuator 64** would not be actuated.

Both the power applied to the at least one **first coil 42**, and the gain and phase of the signal from the **magnetic sensing element 50** in relation to the at least one **first signal 44**, are continuously monitored and stored in a **memory 95** of a **microprocessor 56** as a real-time magnetic signature of the **door 14**. In an embodiment of the **magnetic sensor 10**
5   responsive to relative phase, the phase of the signal from the **magnetic sensing element 50** can be compared with that of the **first signal 44** from the **oscillator 46** with a **phase detector 96** which outputs the associated phase difference to the **microprocessor 56**. The real-time magnetic signature is compared with at least one other comparable magnetic signature -- for example at least one magnetic signature representing the **door 14** prior to an impact or
10   collision, i.e. a normal signature; or at least one magnetic signature representing various impacts or crashes – in order to determine if an associated **safety restraint actuator 64** should be actuated. The at least one normal signature may include magnetic signatures that account for variations in the **magnetic flux 49** as a result of either metal objects proximate to or approaching the **door 14** or variations as a result of corrosion or variations in temperature.
15   The normal signature may be updated over time so as to track minor perturbations of the **door 14**, such as due to temperature or corrosion, which changes would likely occur relatively slowly over time. If the real-time magnetic signature of the **bent metal signal component 72** is sufficiently different from the normal magnetic signature, the **microprocessor 56** would actuate the **safety restraint actuator 64**.

20   Accordingly, the **magnetic sensor 10** is responsive to both small-signal and large-signal disturbances. Small-signal disturbances would include, for example, impacts by relatively small objects such as basketballs or other sporting projectiles, which typically do not cause plastic deformation of the **door 14**, but for which the **door 14** and surrounding weather-seal respond elastically. Large-signal disturbances would include, for example, side impacts that
25   causes plastic deformation of the **door 14**, thereby permanently shifting its magnetic signature. The **magnetic sensor 10** detects the change in magnetic signature from the pre-impact undeformed condition to the post-impact deformed condition. Moreover, the plastically deformed metal is work hardened which causes a change to the permeance thereof, which is sensed by the **magnetic sensor 10**. At the beginning of the impact, prior to plastic
30   deformation of the **door 14**, the **magnetic sensor 10** is able to estimate the impact velocity and severity of the impact using principles of the physics of collisions including conservation of energy and momentum, whereby the response of the **door 14** increases with increasing impact severity. The signal from the **magnetic sensing element 50** comprises information

about both the instantaneous position and the instantaneous velocity of the **door 14**. Moreover, particular polarities of the signal are indicative of particular motions of the **door 14**.

The **magnetic sensor 10** provides a real-time validation of the health and integrity of the respective at least one **first coil 42** and the **second coil 54**, by testing the respective coils for shorts or open conditions, or by using a separate **sense coil 62** to detect the **magnetic flux 49** generated by the at least one **first coil 42**. Moreover, the **magnetic sensor 10** provides a continuous test of the integrity of the **magnetic circuit 38**, including the component under magnetic surveillance, for example the **door 14**.

Referring to **Fig. 1**, in first alternate embodiment of the **magnetic sensor 10**, the at least one **first coil 42** comprises a plurality of **first coils 42.1** and **42.2** at distinct **first locations 48.1** and **48.2**, for example operatively coupled to the **top 18.1** and **bottom 18.2 hinges** that operatively couple the **door 14** to the "**A**" **pillar 16.1**. The separate **first coils 42.1** and **42.2** are driven by separate corresponding **first signals 44.1** and **44.2**, each having a distinct phase with respect to the other, so as to create a **magnetic flux 49** that "rotates" while traveling through the **door 14** to the **magnetic sensing element 50**, whereby an impact to the **door 14** affects the trajectory of the separate signals, thereby affecting the relative distribution of the different phases in the signal sensed by the **magnetic sensing element 50**. The relative phase of the separate **first signals 44.1** and **44.2** is controlled by a **phase control circuit 98** between the **oscillator 46** and one of the **coil drivers 58**, and which, for example, is under control of the **microprocessor 56**. The phase encoding of the respective **first signals 44.1** and **44.2** is similar in theory to the phase encoding of color television and FM radio signals so as to increase the transfer of information along a channel with limited bandwidth. By separately encoding the separate **first signals 44.1** and **44.2**, these respective signals from the **first coils 42.1** and **42.2** -- respectively around the **top 18.1** and **bottom 18.2 hinges** – can be distinguished in the signal from the **magnetic sensing element 50** so as to provide a measure of the vertical location of an impact to the **door 14**.

Referring to **Fig. 3**, in a second alternate embodiment of the **magnetic sensor 10**, the at least one **first coil 42** comprises a **first coil 42** at a **first location 48** and a plurality of **magnetic sensing elements 50**, for example **second coils 54.1** and **54.2** at respective distinct **second locations 52.1** and **52.2** that are each distinct from the **first location 48**. For example, the **first location 48** might be the **bottom hinge 18.2** for improved signal-to-noise ratio, and the **second locations 52.1** and **52.2** might be the **striker 22** and the **top hinge 18.1**

respectively. Such an arrangement would exhibit enhanced sensitivity to impacts proximate to the **bottom hinge 18.2**.

The at least one **first coil 42** or the at least one **magnetic sensing element 50** can be located at a variety of locations and constructed in accordance with a variety of configurations, including but not limited to the following: one or more hinges; the striker; the side impact protection rail or beam inside the **door 14**; around or proximate to the latch/lock mechanism either inside or outside the **door 14**; inside the spot weld line on the top or bottom of the **door 14**; around or proximate to the hinge bolts; on the inner door skin of a plastic or steel **door 14** with the perimeter of the coil nearly matching the perimeter of the **door 14**; around the window glass perimeter; around the entire door structure such as in the air gap surrounding the **door 14** and the opening that one passes through when entering or exiting the vehicle; in a window such as the driver-side window, as a defroster; behind a plastic door handle or trim component, along with associated electronics; around the window glass opening in the **door 14** through which the window is lowered; or in the plastic side view mirror housing for sensing over an extended range, for example to locate steel objects that might pose a side-impact threat.

The magnetic fields generated by these arrangements have a variety of principal orientations, including but not limited to longitudinal, transverse, and vertical. For example, a **first coil 42** can be placed around a **hinge 18** so that the associated magnetic field is either longitudinal or transverse, the former arrangement providing principally a **bent metal flux component 86**, whereas the later arrangement providing a relatively strong **proximity flux component 88**. As another example, a **first coil 42** around the window glass opening in the **door 14** through which the window is lowered generates a vertical magnetic field that circulates around the vehicle along a transverse section thereof. As yet another example, a **first coil 42** around the **door 14** or window in the plane thereof generates a transverse magnetic field that is useful for proximity sensing. Different **first coils 42**, at least one adapted to produce principally a **bent metal flux component 86** and the other adapted to produce principally a **proximity flux component 88** can be used with different associated **first signals 44**, for example, respective first signals with different oscillation frequencies, so as to provide distinguishable **bent metal 72** and **proximity 74 signal components** in the signal from the **magnetic sensing element 50**, wherein the respective signals would be demodulated by respective **synchronous demodulators 70**. For example, in one embodiment, a **10 KHz first signal 44.1** is applied to a **first coil 14.1** on the **top hinge 18.1**,

and a **20 KHz first signal 44.2** is applied to a **first coil 14.2** on the **bottom hinge 18.2**, and both frequencies are sensed substantially simultaneously by different associated **magnetic sensing elements 50** associated with the B-pillar and C-pillar of the **vehicle 12**, respectively.

The operating point of the **magnetic sensor 10**, for example the level of **magnetic flux 49** within the **magnetic circuit 38** and the nominal current supplied to the at least one **first coil 42**, under quiescent conditions, can be adjusted by adjusting the wire gage or number of turns of at least one **first coil 42**.

The system safing or proximity detection can be enhanced by various means, including but not limited to placing a winding around the undercarriage, door opening, or hood of the automobile; placing a winding around the front fender of the automobile; placing a ferrite rod inside the hinge coil, or inside the striker coil for magnetic focusing; placing a ferrite rod coil in the gap or space between the doors; or placing a supplemental **first coil 42** in the side-view mirror molding, which extends sidewards away from the vehicle. An additional system safing supplemental **first coil 42**, with proper phasing and with the magnetic circuit return properly adjusted, would substantially increase the system safing signal performance. For example, this coil could be about 3 inches in diameter and in a plane parallel to the door surface, or wound on a ferrite rod aligned to enhance the launch range and enhance the directivity for system safing. Moreover, by the combination of proximity detection and bent metal detection, together with a self-test of the associated at least one **first coil 42** and the **magnetic sensing element 50**, the **magnetic sensor 10** is able to provide both safing and crash detection functions, thereby precluding the need for a separate crash accelerometer. The **coils 42, 54** and **62** of the **magnetic sensor 10** could, for example, be constructed of wire wound on an associated bobbin, and then placed over an existing component of the vehicle, for example a **hinge 18** or **striker 22**.

The coils or sensing elements may incorporate a ferrite or other high permeability magnetic core. Also, highly-tuned coils can be used for magnetic signal generation. Moreover, the width and length of coil bobbins can be adapted to steer the **magnetic flux 49**. Lastly, the at least one **first coil 42** or the at least one **magnetic sensing element 50** might incorporate ferrite rod coils placed under the vehicle chassis, in the vehicle headliner, in the "A" pillar, or in the "B" pillar, pointing towards the road.

Moreover, the signals associated with the **magnetic sensor 10** can be generated, adapted or processed in a variety of ways, including but not limited to:

1. Setting up an alternate frequency to create system safing on the rear **door 14** to enhance the system safing of the front **door 14**;

2. AM, FM or pulsed demodulation of the magnetic signature;

3. Multi-tone, multi-phase electronics;

4. A magnetically-biased, phase-shift oscillator for low-cost pure sine wave generation;

5. A coherent synthetic or phased-locked carrier hardware- or microprocessor-based system;

6. A system of microprocessor gain-or offset-tuning through D/A then A/D self-adjust or self-test algorithm;

7. Placing a "standard" in the system safing field for magnetic calibration;

8. Inaudible frequencies;

9. Microprocessor-generated crystal stabilized frequencies for stability, including microprocessor D/A converter for coherent sine-wave generation;

10. Wide-band system electronics;

11. Closed loop gain- and phase-control of the signal to a sending-coil (i.e. AGC with the **door 14** acting as a delay line), wherein the gain- and phase-control signals are used as sensor outputs;

12. AC or DC operation, wherein the DC portion of the signal provides information from the net static **magnetic flux 49** of the **door 14** in product with the velocity of the impact, but does not provide proximity information, and the AC approach provides the proximity field and allows the system to be ratiometric with the known and stationary transmitter gain;

13. In accordance with experiments that have shown that the phase varies as the magnetic gain across the **door 14** varies, a phase processor (FM) that has a lower signal-to-noise ratio than a gain processor (AM);

14. Monitoring the power delivered by the coil driver, particularly the bypass power, in order to detect impacts near or at the hinge(s) magnetically energized with the at least one first coil;

15. A series-resonant coil driver-circuit to increase current to flow to the at least one **first coil 42** so as to improve the signal-to-noise ratio, wherein the associated current to the at least one **first coil 42** is monitored to provide a continuous self-test of the at least

one **first coil 42**, as well as a measure of the power drawn by the at least one **first coil 42**; and

16. Using another type of **magnetic sensing element 50**, for example a Hall effect or a Giant Magneto-resistive (GMR) device, instead of a **second coil 54**.

If both front doors are to be protected, then the effects of temperature and component variation may be mitigated by making a ratiometric measurement of comparable signals from one **door 14** relative to another, wherein it is assumed that both doors will not be simultaneously impacted. The ratiometric measurement may also be used to augment the individual measurements from each **door 14**. Furthermore, a common oscillator may be used to generate a common signal used by each associated **first coil 42**, so as to reduce cost and to synchronize the **magnetic flux 49** generated at various locations in the **vehicle 12**.

Whereas the **magnetic sensor 10** has been illustrated herein with the **door 14** as a principal sensing element, the **magnetic sensor 10** may generally be adapted to sensing the integrity of any component of any component capable of conducting **magnetic flux 49**, and would be advantageous for sensing large or long ferromagnetic parts. For example, the **magnetic sensor 10** can be adapted to sensing other body parts, such as fenders, that are attached to the main body of the vehicle by operatively connecting an at least one **first coil 42** between the body part and the main body at the point of attachment.

The proximity or leakage magnetic field comprising the above described **second 88** and **third portions 94** of the **magnetic flux 49** can be useful for detecting magnetically permeable objects proximate to a **vehicle 12**, for example proximate to a **door 14** of a **vehicle 12**; and for detecting the velocity of an object from the affect over time of the object on the permeance of the region proximate to the **vehicle 12**. This provides for what is termed herein a "radar mode" of operation useful for anticipatory collision sensing, with the following features:

1. The "radar mode" can be further augmented by the use of independent carrier frequencies. With frequency differentiation on the magnetic "transmitters" the system can determine and differentiate the incoming "magnetically visible" object's "height off of the earth" relative to the upper and lower hinge position. A SUV will send "more signal" to the upper hinge as compared with a low profile sports car.

2. The incoming object height information will also support pole versus 214 style-hit scenarios.

3. The "radar mode" provides for anticipatory crash sensing, adjacent lane awareness, blind spot awareness, a means for measuring a following distance to a preceding vehicle, a sensor for a collision avoidance system that, for example, could turn the steering wheel as the result of an object detected in the "magnetic fringing field of view" of the automobile door described above, and a sensor for use in a system to automatically center the vehicle between other vehicles in adjacent driving lanes.

4. Some quantity of the magnetic flux generated by the hinge coil will enter the space surrounding the automobile door and return from that space and enter the striker coil.

5. Permeable objects will be detectable as magnetic "leakage" flux lines from the door enter and exit the near-by-permeable object.

6. The list of permeable objects "visible" to the door magnetic fringe field includes, but is not limited to people or relatively large animals, metal objects, automobiles, any object of comparable size to the door and with a distinct permeance, living trees comprising a permeable material.

7. The incoming velocity of these objects can be measured.

8. A state machine can be used to track object motion history and "anticipate" a collision with an object having sufficient velocity to be a danger to the occupant if the velocity does not change. This pre-crash information is sometimes referred to as information at a "negative time".

Referring to **Fig. 4**, a **magnetic sensor 100** comprises a **first coil 42 (L_1)** operatively associated with a **magnetic circuit 38** of a **vehicle body 26** -- schematically illustrated, for example, comprising a **first magnetic path 30** along a **door 14** of the **vehicle 12** and a **second magnetic path 32** -- distinct from the **first magnetic path 30** -- comprising the **body 26**, **structure 34**, or **powertrain 36** of the **vehicle 12**, wherein the **first 30** and **second 32** magnetic paths together constitute a **closed magnetic path 40**. The **first coil 42 (L_1)** is operatively coupled to an **electrical circuit 102** adapted so that the **first coil 42 (L_1)** in cooperation with the **electrical circuit 102** exhibits a resonant or near-resonant condition in association an oscillatory **first signal 44** applied by the **electrical circuit 102** to the **first coil 42 (L_1)**, which generates an associated time-varying **magnetic flux 49**, ϕ, in the **magnetic circuit 38**. In the example illustrated in **Fig. 4**, the **electrical circuit 102** comprises an **oscillator 104** adapted to drive a **first resonant circuit 106** comprising the **first coil 42 (L_1)**, a **first capacitor 108 (C_S)** and a **resistor 110 (R_S)** in series with the **first coil 42 (L_1)**,

wherein the **first signal 44** from the **oscillator 104** is operatively coupled to the **first coil 42** through a **first buffer amplifier 112.**

For example, the **oscillator 104** may generate either a sinusoidal or square wave signal, which can be either mono-polar or bi-polar, although a mono-polar signal is beneficial in simplifying the associated circuitry of the **electrical circuit 102** and it associated power supply. In one embodiment, the **oscillator 104** is adapted to oscillate at **20 KHz** and the associated **first resonant circuit 106** is adapted to have an associated resonant frequency of **10 to 20 KHz.** The associated **electrical circuit 102** is adapted to operate at about half the nominal voltage of the associated power supply of the associated **electrical circuit 102,** so as to provide for continuous operation over the expected operating cycle of the power supply, e.g. vehicle battery. Accordingly, for a a nominal **12** volt power supply, this **oscillator 104** generates a mono-polar signal of **0-6** volts. Generally, the nominal oscillation frequency of the **oscillator 104** may range between DC (no oscillation) and **100 KHz** for a typical **vehicle 12,** but which may be **1 MHz** or higher in a vehicle that has been augmented with supplemental magnetic materials such as mu-metal, ferrite or amorphous metal materials (e.g. METGLAS®). For example, in one set of embodiments, the oscillation frequency of the **oscillator 104** is adapted for the audio to near ultrasonic range of between **5 KHz** and **30 KHz.** The choice of a particular frequency can be affected by electromagnetic compatibility (EMC) issues associated with the **magnetic sensor 100** in the **vehicle 12,** for example, so as to avoid interference with other electronic systems in the vehicle, e.g. the AM radio receiver. In one approach, the frequency spectra of the one or more signals responsive to the **magnetic flux 49,** ϕ are measured responsive to a crash and analyzed so as to determine an upper bound on the frequencies of relevance to the crash for subsequent processing. Then, the associated oscillation frequency of the **oscillator 104** is adapted to be some factor greater than that upper bound frequency of the measured data, e.g. in accordance with the Nyquist criteria. For example, in one embodiment, the oscillation frequency may be adapted to be a factor of at least two times greater than the maximum frequency of interest, for example, a factor of 2.5. The associated nominal resonant frequency of the **first resonant circuit 106** is adapted to be either the same as or different from the oscillation frequency of the **oscillator 104,** depending upon the particular embodiment. The voltage level of the **oscillator 104** and the resistance of the **first resonant circuit 106** are adjusted to provide the level of current through the **first coil 42** (L_1) necessary to provide a desired level of **magnetic flux 49,** ϕ in the associated **magnetic circuit 38.** For a given level of current through the **first coil 42**

(L_1), an increase in the number of turns thereof increases the density of **magnetic flux 49**, ϕ thereby increasing the signal-to-noise ratio of the associated response signals.

Referring to **Fig. 5**, the **first coil 42 (L_1)** can be modeled as an **ideal inductor $L_1{}'$** in series with an **ideal resistor R_{L1}** representing the electrical resistance in the wire of the **first coil 42 (L_1)**, the series combination of which is in parallel with an **ideal capacitor C_{L1}** representing the inter-turn capacitance of the **first coil 42 (L_1)**. The **oscillation frequency f_0** of the **oscillator 104** and the capacitance of the **first capacitor 108 (C_S)** are adapted so that the series combination of the **first coil 42 (L_1)** and the **first capacitor 108 (C_S)** exhibits a resonant or near-resonant condition for at least one condition of the **vehicle body 26**. The inductance $L_1{}'$ of the **first coil 42 (L_1)** is responsive to the associated coil geometry and to the reluctance of the associated **magnetic circuit 38**, both of which can be responsive to a crash. For example, a crash involving the location of the **first coil 42 (L_1)** could distort the coil and possibly cause one or more turns of the coil to become shorted, which would affect the effective inductance $L_1{}'$, resistance R_{L1} and capacitance C_{L1} of the **first coil 42 (L_1)**. Furthermore, a crash affecting elements of the **magnetic circuit 38** can affect the reluctance thereof, which affects the inductance of the **first coil 42 (L_1)** magnetically coupled thereto in accordance with the relationship $L_1{}'=N^2/\mathcal{R}$, wherein $L_1{}'$ is the self-inductance of the **first coil 42 (L_1)**, N is the number of turns of the **first coil 42 (L_1)**, and $\mathcal{R}$ is the magnetic reluctance of the flux path, i.e. the **magnetic circuit 38**, to which the **first coil 42 (L_1)** is magnetically coupled.

A frequency domain representation of the current through a series combination of an inductor **L**, capacitor **C** and resistor **R**, responsive to a source voltage V(jω) having an oscillatory radian frequency ω is given by:

$$I(j\omega) = \frac{-j \cdot \omega \cdot V(j\omega)}{L \cdot \left(\omega^2 - \frac{R}{L} \cdot j\omega - \frac{1}{LC} \right)} \tag{1}$$

and the voltage V_L across the inductor L is given by:

$$V_L(j\omega) = \frac{\omega^2 \cdot V(j\omega)}{\omega^2 - \frac{R}{L} \cdot j\omega - \frac{1}{LC}} = \frac{V(j\omega)}{1 - j \cdot 2 \cdot \zeta \cdot \frac{\omega_n}{\omega} - \left(\frac{\omega_n}{\omega} \right)^2} \tag{2}$$

wherein the resonant frequency ω_n and damping ratio ζ are defined respectively as

$$\omega_n = \frac{1}{\sqrt{LC}} = \frac{1}{2\pi f_n} \text{ and } \zeta = \frac{\sqrt{\left(\frac{R}{L}\right) \cdot (R \cdot C)}}{2} \tag{3}$$

and ω_n and f_n are the radian and natural resonant frequencies respectively. For a component of the oscillatory **first signal 44** at the resonant frequency, i.e. at resonance, the inductive and capacitive reactances of the inductor **L** and capacitor **C** respectively, i.e. $j\omega L$ and $\frac{1}{j\omega C}$

5   respectively, cancel one another, resulting in an impedance **Z=R** of the series combination. At resonance, current **I** through the inductor **L** has a value of **I=V/R**, and the voltage $\mathbf{V_L}$ across the inductor **L** is given by:

$$V_L(j\omega_n) = \frac{V(j\omega_n)}{-j \cdot 2 \cdot \zeta} = j \cdot \frac{V(j\omega_n)}{2 \cdot \zeta} \tag{4}$$

Accordingly, referring to **Fig. 6**, for the **first resonant circuit 106** illustrated in **Fig. 4**,

10   the magnitude of the current $\mathbf{I_{L1}}$ through the **first coil 42** $\mathbf{(L_1)}$, and the corresponding magnitude of the **magnetic flux 49**, ϕ, induced thereby in the **magnetic circuit 38** is maximized when the **first signal 44** from the **oscillator 104** is at the resonant frequency $\mathbf{f_n} = 2\pi\omega_n$ of the **first resonant circuit 106**. For a given level of the **first signal 44**, this series resonant condition maximizes the magnitude of the **magnetic flux 49**, ϕ, which provides for

15   maximizing both the magnitude and signal-to-noise ratio of a crash related response thereto. In addition to providing for an improved signal-to-noise ratio of the response signal, the series resonant condition provides for accommodating lower levels of the **first signal 44** than would otherwise be possible. For example, the level of the **first signal 44** could be one volt, or less, if necessary.

20   Stated in another way, for a given **magnetic flux 49**, ϕ, to be generated in the **magnetic circuit 38** by the **first coil 42** $\mathbf{(L_1)}$ responsive to a **first signal 44**, the necessary magnitude of the **first signal 44** is lower for a series resonant condition than for a non-resonant condition. This is beneficial in an automotive environment -- wherein the battery voltage is subject to substantial variation during its life cycle, depending upon the state of charge, the load levels,

25   and the operativeness of the associated charging system -- by providing for operation using a single-ended nominal **12** volt battery power supply to the **electrical circuit 102** without requiring either an associated voltage magnification circuit or a bi-polar power supply circuit. For example, the series resonant condition provides for operating at a voltage substantially

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less than the nominal battery voltage -- e.g. operating at about **6** volts for a **12** volt nominal battery voltage − so as to provide for uninterrupted sensing during conditions of low battery voltage. This reduces the complexity and cost of the power supply for the associated **electrical circuit 102**, and reduces associated power consumption by the components thereof.

5 Operation at or near resonance is also beneficial in improving the electromagnetic compatibility (EMC) of the **magnetic sensor 100** with other systems.

In one embodiment, the resistance R_S of the **resistor 110 (R_S)** is lower than the resistance R_{L1} of the **first coil 42 (L_1)** so as to reduce power consumption by the **resistor 110 (R_S)** and so as to increase the sensitivity of the current in the **first resonant circuit 106** to changes in

10 the resistance R_{L1} of the **first coil 42 (L_1)**. At resonance, the inductive reactance of the **first coil 42 (L_1)** cancels the capacitive reactance of the **first capacitor 108 (C_S)**, so that the component of current in the **first resonant circuit 106** at the resonant frequency is given by the ratio of the source voltage -- i.e. the voltage of the **first signal 44** from the **oscillator 104** − divided by the total resistance of the **first resonant circuit 106** − i.e. the sum of the

15 resistance R_{L1} of the **first coil 42 (L_1)**, the resistance R_S of the series **resistor 110 (R_S)**, and the resistance of other associated conductors in the **first resonant circuit 106**, e.g. coil leads, cables, printed circuitry, and connector(s). The level of the maximum current level at resonance in the **first resonant circuit 106** can be set to a desired level by adjusting either the total series resistance thereof or the magnitude of the **first signal 44**, or by adjusting both.

20 The magnitude of the associated **magnetic flux 49**, ϕ generated by the **first coil 42 (L_1)** is proportional to the product of the number of turns N of the **first coil 42 (L_1)** times the current I therein, wherein the current I is given by the ratio of the level V of the **first signal 44** divided by the total resistance of the **first resonant circuit 106**, or

$$\phi \sim N \cdot I = \frac{N \cdot V}{R_{Total}} \tag{5}$$

25 For example, the maximum current I or associated maximum **magnetic flux 49**, ϕ may be adjusted to satisfy EMC requirements -- e.g. on radiated power -- by adjusting either the number of turns N or the total resistance R_{Total} without impacting the associated operating voltage V of the system, which, for example, may be a mono-polar +6 volts for a nominal **12** volt battery powered system.

30 The self-capacitance C_{L1} of the **first coil 42 (L_1)** -- which increases with increasing number of turns N of the **first coil 42 (L_1)**, − in combination with the self-inductance $L_1{}'$ of

the **first coil 42 (L_1)**, provides for inherent low-pass filtering of signals applied to or affecting the **first coil 42 (L_1)**. For example, the **first signal 44** from a square wave **oscillator 104**, e.g. a TTL (Transistor Transistor Logic) oscillator, would exhibit harmonics of higher frequency than the fundamental **oscillation frequency f_0**. These harmonics can be attenuated

5   by this effective low-pass filter so as to reduce, or effectively preclude, the generation of components of **magnetic flux 49**, ϕ at the harmonic frequencies – which if otherwise generated might cause undesirable electromagnetic signals -- thereby improving the electromagnetic compatibility (EMC) of the associated **magnetic sensor 100**. Furthermore, increased self-capacitance reduces the electromagnetic susceptibility of the **magnetic sensor**

10   **100** to external interference.

In accordance with a first embodiment of the **magnetic sensor 100.1** – in what is referred to as a transformer mode of operation -- the **magnetic flux 49**, ϕ generated in the **magnetic circuit 38** by the **first coil 42** located at a **first location 48** on the **magnetic circuit 38**, responsive to the **first signal 44** applied thereto, is sensed by a **magnetic sensing element**

15   **50**, e.g. a **second coil 54 (L_2)**, at a **second location 52** on the **magnetic circuit 38**, which generates a **second signal 114** responsive to the reluctance of the **magnetic circuit 38**, for example, responsive to a crash affecting at least one element of the **magnetic circuit 38**, or responsive to a magnetic-flux-influencing object proximate to a **proximity flux component 88** of the **magnetic flux 49** of the **magnetic circuit 38**. The **magnetic sensor 100.1** can be

20   adapted so as to provide for sensing either the magnitude of the **second signal 114** or components thereof, e.g. DC or AC, or for sensing the phase of the **second signal 114** in relation to that of the associated **first signal 44**. For example, in one embodiment that operates at a relatively low frequency, the relative phase between the **first 44** and **second 114** **signals** might be used as a the primary measure to detect a crash.

25   Referring to **Fig. 4**, in accordance with a second embodiment of the **magnetic sensor 100.2**, the voltage level and the signal-to-noise ratio of the **second signal 114** can be enhanced by incorporating a **second resonant circuit 116** comprising a **second capacitor 118 (C_P)** in parallel with the **second coil 54 (L_2)**, adapted to exhibit a resonant or near-resonant condition in combination therewith responsive to an oscillatory **magnetic flux 49**

30   generated responsive to the oscillatory **first signal 44**. The signal from the **second resonant circuit 116** is biased with a DC offset V_{REF} equal to about half the value of the voltage V_{DD} of the associated power supply of the associated **electrical circuit 102'**, so as to provide for a mono-polar **second signal 114** from the **second resonant circuit 116**, thereby simplifying

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the associated circuitry and power supply requirements. The voltage across the parallel combination of the **second coil 54 (L₂)** and the **second capacitor 118 (C_P)** is input to a **second buffer amplifier 120**, the output of which is AC coupled through a **first amplifier 122** and a **first coupling capacitor 124** to a **first demodulator 126**, e.g. a synchronous demodulator, which detects the modulated amplitude of the carrier signal underlying the **second signal 114**. The output from the **first demodulator 126** is directly coupled to a **second amplifier 128**, the output of which is coupled through a **first analog-to-digital converter 130** – e.g. as a **bent metal signal component 72** of the **second signal 114** -- to a **processor 132** for processing as described hereinabove. The output from the **first demodulator 126** is AC coupled through a **second coupling capacitor 134** to a **third amplifier 136**, the output of which is coupled through a **second analog-to-digital converter 138** – e.g. as a **proximity signal component 74** of the **second signal 114** -- to the **processor 132** for processing as described hereinabove.

Referring to **Fig. 7**, the **second coil 54 (L₂)** can be modeled as an **ideal inductor L₂'** in series with an **ideal resistor R_{L2}** representing the electrical resistance of the wire of the **second coil 54 (L₂)**, the series combination of which is in parallel with an **ideal capacitor C_{L2}** representing the inter-turn capacitance of the **second coil 54 (L₂)**. The oscillatory **magnetic flux 49**, ϕ linked with the **second coil 54 (L₂)** induces a voltage therein in accordance with Faraday's law of induction, and this induced voltage is represented in **Fig. 7** by an **oscillatory voltage source E₂** in series with the associated **ideal inductor L₂'**. Although the **second capacitor 118 (C_P)** is connected in parallel with the **second coil 54 (L₂)**, for purposes of modeling the associated **second signal 114**, the **second capacitor 118 (C_P)** and the **second coil 54 (L₂)** can also be considered to be connected in series since these are the only two elements connected to one another. More particularly, as illustrated in **Fig. 7**, the combination of the **second coil 54 (L₂)** and the **second capacitor 118 (C_P)** can be modeled as an **ideal inductor L₂'** in series with an **ideal resistor R_{L2}**, an **oscillatory voltage source E₂**, and with a total capacitance C_{P_Total} given by the sum of the capacitances of the **ideal capacitor C_{L2}** and the **second capacitor 118 (C_P)**, i.e. $C_{P\_Total} = C_{L2} + C_P$. The associated **second resonant frequency** f_{n_2} of the **second resonant circuit 116** is given by:

$$\omega_{n\_2} = \frac{1}{\sqrt{L_2' C_{P\_Total}}} = \frac{1}{2\pi f_{n\_2}} \tag{6}$$

The capacitance of the **second capacitor 118 (C_P)** and the inductance L_2' of the **second coil 54 (L_2)** are adapted, for example, to set the **second resonant frequency f_{n_2}** to correspond to the **oscillation frequency f_0** of the **oscillator 104**. The inductance L_2' of the **second coil 54 (L_2)** is responsive to the associated coil geometry and to the reluctance $\mathcal{R}$ of

5   the associated **magnetic circuit 38**, either of which can be responsive to a crash. For example, a crash involving the location of the **second coil 54 (L_2)** could distort the **second coil 54 (L_2)** and possible cause one or more turns thereof to become shorted, which would affect the effective inductance L_2', resistance R_{L2} and capacitance C_{L2} thereof. Furthermore, a crash affecting elements of the **magnetic circuit 38** can affect the reluctance $\mathcal{R}$ thereof,

10   which affects the inductance of the **second coil 54 (L_2)** operatively associated therewith, in accordance with the relationship $L_2'=N_2^2/\mathcal{R}$, wherein L_2' is the self-inductance of the **second coil 54 (L_2)**, N_2 is the number of turns of the **second coil 54 (L_2)**, and $\mathcal{R}$ is the magnetic reluctance $\mathcal{R}$ of the flux path, i.e. **magnetic circuit 38**, to which the **second coil 54 (L_2)** is coupled. Furthermore, the sensitivity of a change in inductance L_2' to a change in reluctance

15    $\mathcal{R}$ increases with an increasing number of turns N_2. At resonance, i.e. wherein the **magnetic flux 49**, ϕ oscillates at the **second resonant frequency f_{n_2}**, the current through the **second coil 54 (L_2)** and the **second capacitor 118 (C_P)** is maximized to a level that is responsive to the associated series resistance of the **second resonant circuit 116**; and the **second signal 114 (V_{OUT})** -- given by the voltage across the **second capacitor 118 (C_P)** -- is also thereby

20   maximized, as illustrated in **Fig. 8**. The impedance of the parallel elements of the **second resonant circuit 116** is relatively high at resonance, and this high impedance is buffered by the **second buffer amplifier 120** (i.e. a voltage follower) shown in **Fig. 4**, so as to reduce loading thereof by the AC coupled **first demodulator 126**.

The parallel combination of the **second coil 54 (L_2)** and the **second capacitor 118 (C_P)** is

25   beneficial for improving electromagnetic compatibility (EMC) by reducing susceptibility to externally generated electromagnetic fields, wherein at the associated relatively high frequencies, the impedance of the **second capacitor 118 (C_P)** is relatively low, thereby limiting the associated signal levels that can be generated thereacross. Accordingly, the **second resonant circuit 116** provides for enhancing or maximizing the level of the **second**

30   **signal 114** for signals of interest, and for attenuating undesirable signals associated with electromagnetic noise.

It should be understood that the first and second embodiments of the **magnetic sensor 100** can be practiced either jointly in combination with one another, as illustrated in **Fig. 4**, or individually -- one or the other. In one mode of operation, the first and second embodiments of the **magnetic sensor 100** provide distributed crash sensing, wherein the inductance of the

5 **first 42 (L_1)** and **second 54 (L_2) coils**, and the mutual inductance therebetween, is responsive to a crash-induced deflection or deformation of the elements of the associated **magnetic circuit 38**, or responsive to magnetic-field-influencing objects proximate thereto, which thereby affects the **magnetic flux 49**, ϕ therein generated responsive to the **first signal 44** applied to the **first coil 42 (L_1)** at the **first location 48**, and which affects the **second**

10 **signal 114** generated by the **magnetic sensing element 50**, e.g. **second coil 54 (L_2)**, responsive to the **magnetic flux 49**, ϕ thereat. In another mode of operation, referred to as a safing mode, the first and second embodiments of the **magnetic sensor 100** provide for a nominal level of the **second signal 114** for a nominal state of the **magnetic circuit 38**, and changes of the **second signal 114** therefrom provide an indication of changes of or to the

15 elements of the **magnetic circuit 38**, e.g. the **first coil 42 (L_1)**, the **first 30** or **second 32** **magnetic paths**, or the **magnetic sensing element 50 / second coil 54 (L_2)**. Accordingly, the **second signal 114** can be compared with a threshold to determine whether the associated **magnetic sensor 100.1, 100.2** is in an acceptable nominal state prior to the subsequent detection of a crash.

20 In accordance with a third embodiment of the **magnetic sensor 100.3**, the **electrical circuit 102** associated with the **first coil 42 (L_1)** is adapted to sense one or more variables associated with the **first resonant circuit 106**, for example, the voltage across the **first coil 42 (L_1)**, the current through the **first coil 42 (L_1)** as measured by the voltage across the **resistor 110 (R_S)** in series with the **first coil 42 (L_1)**, or the voltage across the **first capacitor**

25 **108 (C_S)**; so as to provide for determining therefrom a measure responsive to the inductance or resistance of the **first coil 42 (L_1)**, for example, the inductance L_1' of the **first coil 42 (L_1)**, the magnitude of the voltage across the **first coil 42 (L_1)**, the magnitude of the current through the **first coil 42 (L_1)**, the phase angle between the voltage across the **first coil 42 (L_1)** and the current through the **first coil 42 (L_1)**, the reactive power applied to the **first coil 42**

30 **(L_1)**, or the real power that is absorbed by the **first coil 42 (L_1)**. The measure responsive to the inductance or resistance of the **first coil 42 (L_1)** may then be used to either diagnose the operativeness of the **first resonant circuit 106** – particularly the **first coil 42 (L_1)** – or to detect the occurrence of a crash in accordance with a self-inductance mode of operation –

particularly impacts proximate to the **first location 48**, (e.g. the **hinge 18** side of the **door 14**) of the **first coil 42 (L_1)**, -- for example, in accordance with the teachings of U.S. Application Serial No. **09/648,606** filed on **August 26, 2000**, now U.S. Patent No. **6,587,048**, which is incorporated herein by reference. For example, the current in the **first coil 42 (L_1)** can be sensed and compared with one or more thresholds to determine if the **first resonant circuit 106** is operating normally for a nominal condition of the **vehicle 12**, or, for example, if one or more turns of the **first coil 42 (L_1)** are shorted. An impact to the **vehicle 12** affecting the **magnetic circuit 28** would modulate the voltage across, the current through, or the inductance of the **first coil 42 (L_1)** to which the above-identified measures are responsive. The measure responsive to the inductance or resistance of the **first coil 42 (L_1)** can be detected and sensed in real time so as to provide for real time detection of the operativeness of the **first resonant circuit 106**, e.g. so as to determine whether or not the **first coil 42 (L_1)** is generating a **magnetic flux 49**, ϕ in the **magnetic circuit 38**. Furthermore, different **magnetic sensors 100** at different locations in the **vehicle 12**, e.g. the A-pillar, B-pillar or C-pillar of the **vehicle 12** may be adapted to verify the operativeness of one another, and thereby provide for mutual safing of different **magnetic sensors 100**.

The current **I** in the **first coil 42 (L_1)** generates a **magnetic flux 49**, ϕ in the associated **magnetic circuit 38**. This **magnetic flux 49**, ϕ stores an associated energy therein which is in balance with both the energy transferred thereto by the **first coil 42 (L_1)**, and with associated energy losses, e.g. resulting from either eddy currents, hysteresis or radiation. A mechanical perturbation of one or more elements of the **magnetic circuit 38**, e.g. the **door 14**, affects this energy balance, resulting in a corresponding affect on the current **I** received or absorbed by the **first coil 42 (L_1)**, and it is believed that the magnitude of this affect is related to the mechanical energy associated with the associated mechanical perturbation.

Stated in another way, the inductance L_1' of the **first coil 42 (L_1)** is responsive to the associated coil geometry (including wire size, number of turns, and turn shape and radii) and to the reluctance of the associated **magnetic circuit 38**. Accordingly, a change to either the **magnetic circuit 38**, or the to coil geometry, -- e.g. responsive to a crash -- will cause an associated change in the associated inductance L_1' of the **first coil 42 (L_1)**, which in turn causes an associated change in the **impedance Z_L** thereof responsive to an oscillatory signal from the **oscillator 104**, which in turn causes an associated change in the **impedance Z** of the **first resonant circuit 106** to which the **first signal 44** from the **oscillator 104** is applied. Accordingly, for a **first signal 44** having a constant amplitude V, the resulting current **I**

through the **first coil 42 (L₁)** given as $I = V / Z$ will vary responsive to the value of Z, with is responsive to and indicative of the mechanical perturbation of either the associated **magnetic circuit 38** or the **first coil 42 (L₁)**.

Furthermore, certain types of crashes, e.g. pole impacts, the extent to which a crash

5   induced perturbation of the **magnetic circuit 38** influences the resulting current **I** in the **first coil 42 (L₁)** is responsive to the proximity of the crash location to the **first coil 42 (L₁)**. Accordingly, in accordance with one embodiment, the magnitude of the variation in current **I** in the **first coil 42 (L₁)** can be used as a measure of the proximity of the crash to the **first coil 42 (L₁)**. In accordance with another embodiment, the variation in current **I** in the **first coil 42**

10   **(L₁)** in relation to the variation in the associated signal from one or more associated **magnetic sensing elements 50** can be used to determine the location of the crash in relation to the locations of the **first coil 42 (L₁)** and the one or more associated **magnetic sensing elements 50**. Generally, the modulation of the current **I** in the **first coil 42 (L₁)** is useful for sensing crash severity and location, and for verifying the operativeness of the **first coil 42 (L₁)**. By

15   relatively increasing or maximizing the current **I** in the **first coil 42 (L₁)** using a **first resonant circuit 106** as described hereinabove, the associated detection sensitivity is relatively increased or maximized.

Referring to **Fig. 4**, in accordance with a first embodiment of a subsystem for sensing one or more variables associated with the **first resonant circuit 106**, both the voltage across the

20   **first coil 42 (L₁)**, and the voltage across the **resistor 110 (Rₛ)**, are sensed, the latter of which provides a measure of the current **I** through the **first coil 42 (L₁)**. The voltage across the **first coil 42 (L₁)** is input to a **differential amplifier 140** operatively coupled to **third analog-to-digital converter 142**, either directly or through a **second demodulator 144**, and the output of the **third analog-to-digital converter 142** is input to the **processor 132**. The voltage V_{RS}

25   across the **resistor 110 (Rₛ)** is input to a **fourth amplifier 146** operatively coupled to **fourth analog-to-digital converter 148**, either directly or through a **third demodulator 150**, and the output of the **fourth analog-to-digital converter 148** is input to the **processor 132**. Notwithstanding that the **fourth amplifier 146** is illustrated as a single-ended amplifier, it should be understood that the **fourth amplifier 146** may also be adapted as a differential

30   amplifier, with the differential inputs thereof adapted to measure the voltage signal across the **resistor 110 (Rₛ)**.

It should be understood, that the **analog-to-digital converters 130, 138, 144** and **148** would cooperate with associated low pass anti-aliasing filters either incorporated therein, or

incorporated in other signal conditioning elements that preprocess the signal(s) thereto, so as to prevent high frequency information from aliasing as corresponding lower frequency information in the sampled signals. For example, in accordance with the Nyquist sampling criteria, the sampling frequency of the **analog-to-digital converters 130, 138, 144** and **148**

5 would be at least twice as great as the cut-off frequency of the associated anti-aliasing filter. It is beneficial to adapt the anti-aliasing filter, for example, by using a single pole anti-aliasing filter, so as to provide for avoiding excessive phase shift or delay in the filtered signal, so as to provide for an associated relatively fast step response.

The **second 144** and **third 150 demodulators**, if present, provide for detecting one or

10 more of the magnitude, the phase and the relative phase of the respective input signals to the respective **demodulators 144, 150**. More particularly, each respective input signal comprises a carrier at the **oscillation frequency f$_0$**, which carrier is modulated by a respective modulation signal, and the **demodulators 144, 150**, if present, provide for generating one or measures of amplitude or phase responsive to associated characteristics of the respective

15 modulation signal. Depending upon their configuration, the **second 144** and **third 150 demodulators**, if present, may be connected either directly to the **processor 132**, e.g. to one or more digital inputs, or through associated **third 142** and **fourth 148 analog-to-digital converters**. Furthermore, the functions of the **second 144** and **third 150 demodulators** could be combined in a single demodulator that generates either analog or digital output

20 signals, or both, and is which appropriately connected to the **processor 132**. Yet further, one or more demodulation functions could also be carried out directly by the **processor 132** on one or more of the respective input signals. Yet further, one or all of the **demodulators 126, 144** or **150** (e.g. the **second demodulator 144** as illustrated in **Fig. 4**) may be operatively coupled to the **oscillator 104** so as to facilitate phase processing of the associated signal(s).

25 For example, the relative phase of the current through and voltage across the **first coil 42 (L$_1$)** can be affected by either the opening of the **door 14**, or an impact thereto resulting from a crash.

The voltage **V$_{RS}$** across the **resistor 110 (R$_S$)** provides a measure of the current **I** therethrough, given by $I = V_{RS} / R_S$, which is also a measure of the current through the **first**

30 **coil 42 (L$_1$)** in series therewith. The measure of current **I** will be responsive to the total resistance **R$_{Total}$** of the **first resonant circuit 106** and to the sum of the inductive and capacitive reactances of the **first coil 42 (L$_1$)** and the **first capacitor 108 (C$_S$)** respectively, the latter of which sum to zero at resonance. Increasing the gain of the **fourth amplifier 146**

increases the sensitivity of the measure of current **I** to the resistance R_{L1} of the **first coil 42 (L_1)**, and accordingly, the sensitivity to detecting whether one or more turns thereof are shorted. A shorting of one or more coils of the **first coil 42 (L_1)** causes the associated current **I** to increase. Furthermore, if one or more turns of the **first coil 42 (L_1)** are shorted, then the

5   self-inductance L_1' of the **first coil 42 (L_1)** would also be affected, e.g. reduced, which would in turn affect the current **I** and the associated measure thereof, and the total reactance of the **first resonant circuit 106** would become increasingly capacitive reactive, thereby affecting the phase of the current **I** through the **resistor 110 (R_S)** relative to the voltage of the **first signal 44** applied by the **oscillator 104**. The self-inductance L_1' of the **first coil 42 (L_1)** is

10   also responsive to the reluctance $\mathcal{R}$ of the associated **magnetic circuit 38**, changes to which -

- e.g. responsive to a crash or a proximate object -- also affect the current **I** and the associated measure thereof. It is expected that the sensitivity of the self-inductance L_1' of the **first coil 42 (L_1)** to changes in the reluctance $\mathcal{R}$ of the associated **magnetic circuit 38** can be increased by increasing the number of turns of the **first coil 42 (L_1)**. Additional **fourth**

15   **amplifiers 146** and associated electronics may be added to provide for a plurality of current responsive signals, each having a different level of associated amplifier gain and resulting sensitivity. For example, a different sensitivity might be used for detecting changes of resistance R_{L1} -- e.g. caused by shorted turn condition -- of the **first coil 42 (L_1)** than might be used for detecting crash-induced changes to the inductance L_1' thereof. Alternately, a

20   single gain-controllable **fourth amplifier 146** could be used, with the gain thereof controlled by the **processor 132**.

For a pure inductor **L**, the relationship between the voltage V_L across to the current I_L through the inductor **L** is given by:

$$V_L = L \cdot \frac{dI_L}{dt} \text{ or, in the frequency domain, } V_L(j\omega) = j\omega \cdot L \cdot I(j\omega) \tag{7}$$

25   Accordingly, for an ideal inductor, the current **I** therethrough lags the voltage V_L thereacross by 90 degrees, and in the frequency domain, the inductance is given by:

$$L = \frac{V_L(j\omega)}{j\omega \cdot I(j\omega)} \tag{8}$$

Alternately, in the time domain:

$$L = \frac{\int_{t_0}^{t_1} V_L(t) \cdot dt}{I_L(t_1) - I_L(t_0)} \tag{9}$$

However, for a real inductor, e.g. **first coil 42 (L_1)** represented by a the second-order system illustrated in **Fig. 5**, the phase angle between the current through the inductor L_1 and the voltage thereacross will be different from 90 degrees. Accordingly, the phase angle

5   between the measure of current **I** -- from the voltage across the **resistor 110 (R_S)** – and the voltage V_L across the **first coil 42 (L_1)** can be used to augment the calculation of the inductance of the **first coil 42 (L_1)**, so as to account for the affects of the associated resistance R_{L1} and/or capacitance C_{L1}. Other changes to the resistance of the **first resonant circuit 106**, i.e. changes external to the **first coil 42 (L_1)**, e.g. changes to the resistance of an

10   associated connector -- e.g. as caused by a loose connector or faulty connection -- would not affect the phase angle between the measure of current **I** and the voltage across the **first coil 42 (L_1)**, but would affect both the magnitude of the current **I** and the phase angle of this current **I** relative to the **first signal 44**.

The **processor 132** senses the voltage V_L and current **I** signals in real time in order to

15   either diagnose a failure of or change to either the **first coil 42 (L_1)** or elements of the associated **first resonant circuit 106**, or to discriminate a crash or other condition affecting the magnetic circuit **38**. In addition to using the magnitudes of the voltage V_L and current **I**, the processor can also use the relative phase thereof, or the phase of either the voltage V_L of current **I** relative to that of the **first signal 44**, in order to determine, for example, the

20   inductance L_1' or impedance of the **first coil 42 (L_1)**, the resistance R_{L1} thereof, or the resistance of the **first resonant circuit 106**.

The **processor 132** may further determine the power applied to the **first coil 42 (L_1)** – either reactive (V*I), real (V*I*$\cos(\theta)$), or both -- which can be used as addition information for either failure detection, crash sensing, or sensing some other measure responsive to the

25   reluctance $\mathcal{R}$ of the **magnetic circuit 38**.

The quality factor, or **Q**, of the **first resonant circuit 106** is related to the bandwidth of the **magnetic sensor 100**, and is affected by the resistance of the **first resonant circuit 106** – i.e. either the intrinsic resistance of the coil, the resistance of the associated series **resistor 110 (R_S)**, or the equivalent series resistance (ESR) of the associated **first capacitor 108 (C_S)**.

30   Accordingly, the **Q** of the **first resonant circuit 106** can be set or adjusted by setting or

adjusting the associated resistance of the **first resonant circuit 106**, for example, either by adjusting the intrinsic resistance of the **first coil 42 (L₁)** – which is described more fully hereinbelow, -- or by adjusting the resistance of the series **resistor 110 (Rₛ)**. The overall sensitivity of the **magnetic sensor 100** to associated magnetic disturbances in or to the **magnetic circuit 38** is affected by the relative amount by which the oscillation frequency differs from the resonant frequency of the **first resonant circuit 106**, and this sensitivity to that change is affected by the **Q** of the **first resonant circuit 106**. For example, this sensitivity or gain is highest when the oscillation frequency is equal to the resonant frequency, and is reduced as the relative difference increases, as illustrated in **Fig. 6**, wherein the sensitivity of this reduction to changes in the relative frequency difference is directly related to the **Q** of the **first resonant circuit 106** – as Q increases, sensitivity becomes more sensitive to the relative frequency difference.

In accordance with a second embodiment of a subsystem for sensing one or more variables associated with the **first resonant circuit 106**, the voltage V_L across the **first coil 42 (L₁)** is sensed as described hereinabove, without separately sensing the voltage V_{RS} across the **resistor 110 (Rₛ)**. The voltage V_L across the **first coil 42 (L₁)** will be responsive to the current **I** through the **first coil 42 (L₁)** as follows:

$$V_L = I \cdot Z_L \tag{10}$$

where Z_L is the impedance of the **first coil 42 (L₁)**. The current **I** through the **first resonant circuit 106** is given by:

$$I = \frac{V}{Z_L + Z_{CS} + R_S} \tag{11}$$

where **V** is the voltage of the **first signal 44**, Z_{CS} is the impedance of the **first capacitor 108 (Cₛ)**, and R_S is the impedance of the **resistor 110 (Rₛ)** (if present). The impedance Z_L of the **first coil 42 (L₁)** is then given as a function of the voltages **V** of the **first signal 44** and V_L across the **first coil 42 (L₁)** as follows:

$$Z_L = \frac{Z_{CS} + R_S}{\dfrac{V}{V_L} - 1} \tag{12}$$

For example, assuming that the voltage **V** of the **first signal 44**, the impedance Z_C the **first capacitor 108 (Cₛ)**, and the impedance R_S of the **resistor 110 (Rₛ)** (if present) are

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constant, then the impedance Z_L of the **first coil 42 (L_1)** is given as a function of the voltage V_L thereacross.

In accordance with a third embodiment of a subsystem for sensing one or more variables associated with the **first resonant circuit 106**, the voltage V_{RS} across the **resistor 110 (R_S)** is sensed as described hereinabove, without separately sensing the voltage V_L across the **first coil 42 (L_1)**. The voltage V_{RS} across the **resistor 110 (R_S)** is responsive to the current I_L through the **first coil 42 (L_1)** as described hereinabove, and is responsive to the condition of resonance as illustrated in **Fig. 6**. Furthermore, the relationship between the voltage V_{RS} across the **resistor 110 (R_S)** – or the associated measure of current I therethrough -- and the voltage V of the **first signal 44** is responsive to the impedances Z_L and Z_{CS} of the **first coil 42 (L_1)** and **first capacitor 108 (C_S)** respectively and the resistance R_S of the **resistor 110 (R_S)**, e.g. as illustrated by equation (11) hereinabove.

In accordance with a fourth embodiment of a subsystem for sensing one or more variables associated with the **first resonant circuit 106**, the voltage V_C across the **first capacitor 108 (C_S)** -- or the voltage ($V_C + V_{RS}$) across the series combination of the **first capacitor 108 (C_S)** and **resistor 110 (R_S)** -- can be sensed as an alternative to, or in addition to, sensing the voltage V_L across the **first coil 42 (L_1)** or the voltage V_{RS} across the **resistor 110 (R_S)**. For example, the voltage V_L across the **first coil 42 (L_1)** is given by:

$$V_L = V_1 - (V_{CS} + V_{RS}) \qquad (13)$$

Referring to **Figs. 4** and **9**, in accordance with a fifth embodiment of a subsystem for sensing one or more variables associated with the **first resonant circuit 106**, the relative phase of **third 152** and **fourth 154 signals**, e.g. the voltage V_L across the **first coil 42 (L_1)** and the voltage V_{RS} across the **resistor 110 (R_S)**, is determined directly by the **processor 132** by an associated **process 900**, wherein the **third 152 (V_L)** and **fourth 154 (V_{RS}) signals** are input to the **processor 132** through respective **third 142** and **fourth 148 analog-to-digital converters**, are read by the processor in step (**902**). In step (**904**), if a phase timer has been previously started, then in step (**906**) the phase timer is incremented, wherein the phase timer measures the time difference between associated positive-going zero crossings of the **third 152 (V_L)** and **fourth 154 (V_{RS}) signals**, and thereby is used to generate a measure of the relative phase thereof. In step (**910**), a **first average value** $\overline{V}_L$ of the **third signal 152 (V_L)** is determined, for example, using a running average or low pass filtering process. In step (**912**), a **second average value** $\overline{V}_{RS}$ of the **fourth signal 154 (V_{RS})** is determined, for example,

using a running average or low pass filtering process, e.g. similar to that used in step (910). The respective average values $\overline{V}_L$ and $\overline{V}_{RS}$ represent the long term average values of the respective **third 152 (V_L)** and **fourth 154 (V_{RS}) signals**, which, for example, for an associated mono-polar **electrical circuit 102** would be corresponding non-zero bias values about which oscillate the associated oscillatory **third 152 (V_L)** and **fourth 154 (V_{RS}) signals**. For example, for a sinusoidal signal oscillating between extremes of +1 and +5 volts, the associated average value would be +3 volts, or its equivalent representation in the **processor 132**. Then, in step (914), the **third signal 152 (V_L)** is compared with the associated **first average value** $\overline{V}_L$, and if the **third signal 152 (V_L)** is greater, then, in step (916), an associated **first binary value** $V_L^{\bullet}$ is set to one; otherwise, in step (918), the associated **first binary value** $V_L^{\bullet}$ is set to zero. Then, in step (920), if the **first binary value** $V_L^{\bullet}$ has undergone a transition from zero to one -- thereby exhibiting a leading edge, and indicating the occurrence of a positive-going zero crossing of the **third signal 152 (V_L)**, -- then, in step (922), the phase timer is reset to an initial value, e.g. zero, and then started. Following step (922), or otherwise from step (920), in step (924), the **fourth signal 154 (V_{RS})** is compared with the associated **second average value** $\overline{V}_{RS}$, and if the **fourth signal 154 (V_{RS})** is greater, then, in step (926), an associated **second binary value** $V_{RS}^{\bullet}$ is set to one; otherwise, in step (928), the associated **second binary value** $V_{RS}^{\bullet}$ is set to zero. Then, in step (930), if the **second binary value** $V_{RS}^{\bullet}$ has undergone a transition from zero to one – thereby exhibiting a leading edge, and indicating the occurrence of a positive-going zero crossing of the **fourth signal 154 (V_{RS})**, -- then in step (932) the value of the phase timer is stored, and the process repeats with step (902). Otherwise, from step (930), the process repeats with step (902). A stored value of the phase timer less than a value corresponding to a period of a half wave length corresponds to the **third signal 152 (V_L)** lagging with respect to the **fourth signal 154 (V_{RS})**; a stored value of the phase timer greater than the value corresponding to a period of a half wave length corresponds to the **third signal 152 (V_L)** leading with respect to the **fourth signal 154 (V_{RS})**; and a stored value of the phase timer equal to the value corresponding to a period of a half wave length corresponds to the **third signal 152 (V_L)** being 180 degrees out of phase with respect to the **fourth signal 154 (V_{RS})**.

Referring to **Fig. 10**, in accordance with a sixth embodiment of a subsystem for sensing one or more variables associated with the **first resonant circuit 106**, the relative phase of the **third 152 (V_L)** and **fourth 154 (V_{RS}) signals** can be measured with an apparatus comprising

first 156 and second 158 phase-locked-loops (PLL), the respective inputs of which are operatively coupled to the respective third 152 (V_L) and fourth 154 (V_{RS}) signals, the respective outputs of which are coupled to an exclusive-OR (XOR) gate 160, the output of which is used to control gate of a counter 162, which counter 162 may be incorporated in, or
5   implemented in software by, the processor 132. More particularly, the first phase-locked-loop 156 (PLL) generates a first coherent square wave 164 that is phase-aligned with the third signal 152 (V_L), and the second phase-locked-loop 158 (PLL) generates a second coherent square wave 166 that is phase-aligned with the fourth signal 154 (V_{RS}). The output signal 168 of the exclusive-OR (XOR) gate 160 is ON when the values of the first
10   164 and second 166 coherent square waves are different − corresponding to periods of associated relative phase difference, -- and is OFF when the values of the first 164 and second 166 coherent square waves are the same. The counter 162 is reset responsive to a positive-going leading edge of the output signal 168, and thereafter continues to count at a fixed rate until the output signal 168 returns to an OFF condition, at which time the
15   associated value of the counter is stored. Accordingly, the counter 162 measures the period of time corresponding to the phase difference of the third 152 (V_L) and fourth 154 (V_{RS}) signals. A stored counter value less than a value corresponding to a period of a half wave length corresponds to the third signal 152 (V_L) lagging with respect to the fourth signal 154 (V_{RS}); a stored counter value greater than the value corresponding to a period of a half wave
20   length corresponds to the third signal 152 (V_L) leading with respect to the fourth signal 154 (V_{RS}); and a stored counter value equal to the value corresponding to a period of a half wave length corresponds to the third signal 152 (V_L) being 180 degrees out of phase with respect to the fourth signal 154 (V_{RS}).

Referring to Fig. 11, in accordance with a fourth embodiment of the magnetic sensor
25   100.4, the capacitance C_S of the first capacitor 108 (C_S) in the embodiments illustrated in Fig. 4 can be distributed amongst a plurality of capacitors, for example, third 170 (C_1) and fourth 172 (C_2) capacitors, each connected to different ends of the first coil 42 (L_1) − i.e. so that the first coil 42 (L_1) is connected between the third 170 (C_1) and fourth 172 (C_2) capacitors,-- wherein the capacitances of the third 170 (C_1) and fourth 172 (C_2) capacitors
30   are adapted so that the capacitance of their combination in series is equal to the capacitance C_S of the first capacitor 108 (C_S), as follows:

$$C_S = \frac{C_1 \cdot C_2}{C_1 + C_2} \tag{14}$$

This distribution of capacitance to both sides of the **first coil 42 (L_1)** is beneficial in providing for tolerating shorts to either power or ground in the conductors that couple the **first coil 42 (L_1)** to the associated **electrical circuit 102**, which shorts might otherwise damage the associated **electrical circuit 102**, but which instead are readily detected by the above described embodiments for sensing one or more variables associated with the **first resonant circuit 106**. For example, typically the **first coil 42 (L_1)** would be connected to the associated **electrical circuit 102** with a cable or wiring harness, which might be susceptible to the above described faults during assembly or operation of the **vehicle 12**. The resonance conditions of the **first resonant circuit 106** are otherwise as described hereinabove for a **first resonant circuit 106** incorporating a single **first capacitor 108 (C_S)**.

In accordance with a fifth embodiment of the **magnetic sensor 100.5**, the resistance R_{L1} of the **first coil 42 (L_1)** increases if the wire gauge thereof is reduced, or the number of turns N thereof is increased. If the resistance R_{L1} of the **first coil 42 (L_1)** is sufficient to limit the maximum current I in the **first resonant circuit 106** to an acceptable level, then the **resistor 110 (R_S)** can be eliminated from the **first resonant circuit 106**. This arrangement also provides for improved sensitivity of the voltage (V_L) across the **first coil 42 (L_1)** to changes in the resistance R_{L1} of the **first coil 42 (L_1)**, e.g. as might be caused by a shorting of one or more turns within the **first coil 42 (L_1)**; which otherwise for a system incorporating a **resistor 110 (R_S)** in the **first resonant circuit 106**, increases as the ratio of the resistance R_{L1} to the resistance R_S increases. For example, the intrinsic resistance of the **first coil 42 (L_1)** can be set to a value between about **0.1** ohms and **10** ohms by adjusting the associated wire size (gauge) and/or length of wire (number of turns). For a **first coil 42 (L_1)** of **60** turns, if the total intrinsic resistance thereof were **0.1** ohms, the resistance per turn would be **0.0001666** ohms per turn; whereas if the total intrinsic resistance were **10** ohms, the resistance per turn would be **0.16** ohms per turn, the latter of which would be substantially easier to measure. In addition to being affected by the total intrinsic resistance of the **first coil 42 (L_1)**, the detectability of shorted turns is also affected by resistance of the series **resistor 110 (R_S)** in relation to that of the **first coil 42 (L_1)**, and can be improved by increasing the gain of the **fourth amplifier 146** used to amplify the voltage across the **resistor 110 (R_S)**.

In accordance with the above described embodiments, the **oscillation frequency f_0** may be adapted to provide for a resonant or near-resonant condition at the nominal state of the **vehicle 12** and the associated **magnetic circuit 38** (i.e. pre-crash); or may be adapted to be off-resonance for the nominal condition of the **vehicle body 26** and the associated **magnetic**

circuit 38, and then to provide for a resonant or near-resonant condition responsive to a crash, as a result of an associated shift in the inductance L_1' or L_2' of the **first coil 42 (L_1)** or the **second coil 54 (L_2)**. Furthermore, the **magnetic sensor 100** could incorporate a plurality of distinct frequencies, different frequencies being adapted to provide for an associated

5   resonance for different associated conditions of the **vehicle body 26**.

Referring to **Fig. 4**, in accordance with a sixth embodiment of the **magnetic sensor 100.6**, the **oscillator 104** may be adapted to be controllable responsive to a **signal 174** from the **processor 132**. For example, the **oscillator 104** may be a voltage controlled oscillator (VCO). In operation, the **oscillation frequency f_0** of the **oscillator 104** is swept through – in

10   either a stepwise or continuous fashion -- the associated resonant frequency f_n of the **first resonant circuit 106**. An output from the oscillator can be coupled to the **processor 132**, either directly, or, if analog, through a **fifth analog-to-digital converter 176**, so as to provide a measure of, the output from the oscillator, for example, the **oscillation frequency f_0** or associated level **V** of the **first signal 44**. For example, the **processor 132** could directly

15   sense the **first signal 44**, and then determine the associated level **V** and **oscillation frequency f_0** directly therefrom. The particular resonant frequency can then be identified as the **oscillation frequency f_0** for which the voltage across either the **first coil 42 (L_1)**, the **first capacitor 108 (C_S)** or the **resistor 110 (R_S)** is maximized, and the associated inductance L_1' of the **first coil 42 (L_1)** can be identified therefrom. Similarly, the associated inductance L_2'

20   of the **second coil 54 (L_2)** can be identified after determining by similar means the resonant frequency f_{n_2} of the **second resonant circuit 116**.

The particular operating point on the frequency response characteristic – e.g. as illustrated in **Fig. 6** -- of the **first resonant circuit 106** will affect the amount of power transferred to the **magnetic circuit 38** by the **oscillator 104 / first buffer amplifier 112**. In one

25   embodiment, upon initialization of the **magnetic sensor 100**, the resonant frequency of the **first resonant circuit 106** and the nature of the associated frequency response is identified by sweeping the oscillation frequency and monitoring the response from the associated **magnetic sensing element 50**, generally as described hereinabove, either using the primary **oscillator 104** as the signal source, or another oscillator, so as to provide for measuring both

30   the resonant frequency of the **first resonant circuit 106**, and its associated frequency response. If the resulting measured resonant frequency is different from the nominal **oscillation frequency f_0** of the **oscillator 104**, then thereafter, when operating at the nominal **oscillation frequency f_0**, one or more software or hardware parameters or variables would be

adjusted, e.g. in accordance with a correction factor, to accommodate the associated degradation in gain caused by operating with an **oscillation frequency** f_0 that differs from the resonant frequency of the associated **first resonant circuit 106.** Accordingly, this embodiment provides for adapting to relatively long term changes in the **magnetic sensor 100,** for example, as might result from either production variability, temperature, or aging. A warning can be generated or activated, e.g. via an indicator or alarm, if the magnitude of the associated correction factor exceeds a threshold, e.g. indicative of the need for maintenance or repair.

For example, if the **first coil 42 (L_1)** were an ideal inductor having an inductance of L_1, then if the resonant frequency were determined to be f_n, then the inductance L_1 would be given by:

$$L_1 = \frac{1}{4 \cdot \pi^2 \cdot f_n^2 \cdot C_S} \tag{15}$$

In accordance with another aspect of the sixth embodiment, either the **oscillator 104** or an associated amplifier, e.g. the **first buffer amplifier 112,** may be controlled responsive to a **signal 174** from the **processor 132,** or another controller, so as to control the level of **current** I to the **first coil 42 (L_1),** as sensed from the voltage V_{RS} across the **resistor 110 (R_S).** By operating at least near resonance, the impedance of the **first resonant circuit 106** is at least substantially resistive, which simplifies the associated control algorithm for controlling the level of current I. For example, the current I may be controlled to a constant value using a relatively low bandwidth control algorithm which is fast enough so as to correct for long term variations, e.g. resulting from production variations, temperature effects, or aging, but is slow enough so as to not adversely affect a crash induced perturbation or variation of the current I. Accordingly, this closed loop current control system provides for maintaining the nominal level of current I through the **first coil 42 (L_1)** so as to correspondingly maintain an associated nominal level of **magnetic flux 49,** ϕ in the associated **magnetic circuit 38,** thereby accommodating changes to the **first resonant circuit 106** that might affect the resonant frequency thereof, and accordingly, might otherwise adversely affect the level of current I as a result of the inherent frequency response of the **first resonant circuit 106** and its associated bandwidth.

Responsive to the detection of a crash, or other condition affecting the **vehicle body 26** or associated **magnetic circuit 38,** or responsive to the detection of a failure of a component of

the **magnetic sensor 100**, by any of the above described embodiments, the **processor 132** can then either actuate an associated **safety restraint actuator 64**, or an associated **indicator 178**, as necessary to either protect or inform an occupant of the **vehicle 12**.

Referring to **Fig. 12**, the current **I** in the **first coil 42** may be used to provide a measure of the **opening angle** α of the **door 14** as a result of the affect thereof on the reluctance of the associated **magnetic circuit 38**. Alternately, or in addition to this measure, the **opening angle** α of the **door 14** may be detected by providing a **third coil 180** operatively coupled to the **door 14**, which cooperates with the **first coil 42** operatively coupled to a relatively fixed portion of the **vehicle 12**, e.g. about the **axis 182** of a fixed portion of a door **hinge 18**. For example, the **third coil 180** could be located about an **axis 184** that rotates with the **door 14**, e.g. an axis of a moveable portion of a **hinge 18**. The **third coil 180** is located either in the near field of the **first coil 42**, or in the associated **magnetic circuit 38** so as to be rotatable in relation to the direction of the **magnetic flux 49**, ϕ therein, so that a signal from the **third coil 180** is responsive to the **magnetic flux 49**, ϕ generated by the **first coil 42** responsive to a current **I** applied thereto, and is responsive to the mutual coupling of the **magnetic flux 49**, ϕ between the **first 42** and **third 180 coils**. This mutual coupling is responsive to the alignment between the **first 42** and **third 180 coils**, which depends upon the **opening angle** α of the **door 14**. A signal from the **third coil 180** can provide a measure of whether the **door 14** is open and/or a measure of the associated **opening angle** α. The **third coil 180** can also be used a **sense coil 62** as described hereinabove, which can provide an indication of the operativeness of the **first coil 42**. The **third coil 180** can also be used as a sensor in a feedback control system (e.g. an automatic gain control (AGC)) which is adapted to control the level of **magnetic flux 49**, ϕ generated by the **first coil 42**, which can also be adapted so that one or more signals from the associated control system provide either a measure of the door opening status or **angle** α, or a measure of energy flow responsive to a crash, or both.

Referring to **Fig. 13**, in accordance with another embodiment, a **vehicle 12** incorporates a **magnetic crash sensing system 200** comprising **first 202** and **second 204 magnetic sensors** operatively associated with the **left 206** and **right 208 sides** of the **vehicle 12**, respectively.

The **first magnetic sensor 202** comprises an associated **oscillator 210.1** operatively coupled to an associated **coil driver 212.1** which is operatively coupled to an associated **first resonant circuit 214.1** comprising an associated **first coil 216.1** in series with an associated **first capacitor 218.1**, wherein the associated **first coil 216.1** is located at an associated **first**

location 220.1 on an associated **magnetic circuit 222.1** thereof. The **first magnetic sensor 202** further comprises an associated **magnetic sensing element 224.1** comprising, for example, an associated **second coil 224.1'**, which is illustrated as part of a **second resonant circuit 226.1** further comprising a **second capacitor 228.1** in parallel with the **second coil 224.1**. The associated **magnetic sensing element 224.1** is located at an associated **second location 230.1** on the associated **magnetic circuit 222.1**. For example, the **first 220.1** and **second 230.1 locations** respectively are illustrated as respectively comprising a **hinge 18** and a **striker 22** of a **door 14** on the **left side 206** of the **vehicle 14**. The output of the **second resonant circuit 226.1** is amplified/buffered by an associated **first amplifier 232.1**, e.g. a differential amplifier, the output of which is processed by an associated **preprocessing circuit 234.1**, for example, comprising elements comparable to the **first amplifier 122**, **first coupling capacitor 124**, **first demodulator 126**, **second coupling capacitor 134**, **second amplifier 128**, and **third amplifier 136** as illustrated in **Fig. 4** and described hereinabove. The output of the associated **preprocessing circuit 234.1** is converted to digital form by at least one associated **first analog-to-digital converter 236.1**, and the signal therefrom input to an associated **processor 238**.

The **second magnetic sensor 204** comprises an associated **oscillator 210.2** operatively coupled to an associated **coil driver 212.2** which is operatively coupled to an associated **first resonant circuit 214.2** comprising an associated **first coil 216.2** in series with an associated **first capacitor 218.2**, wherein the associated **first coil 216.2** is located at an associated **first location 220.2** on an associated **magnetic circuit 222.2** thereof. The **second magnetic sensor 204** further comprises an associated **magnetic sensing element 224.2** comprising, for example, an associated **second coil 224.2'**, which is illustrated as part of a **second resonant circuit 226.2** further comprising a **second capacitor 228.2** in parallel with the **second coil 224.2**. The associated **magnetic sensing element 224.2** is located at an associated **second location 230.2** on the associated **magnetic circuit 222.2**. For example, the **first 220.2** and **second 230.2 locations** respectively are illustrated as respectively comprising a **hinge 18** and a **striker 22** of a **door 14** on the **right side208** of the **vehicle 14**. The output of the **second resonant circuit 226.2** is amplified/buffered by an associated **first amplifier 232.2**, e.g. a differential amplifier, the output of which is processed by an associated **preprocessing circuit 234.2**, for example, comprising elements comparable to the **first amplifier 122**, **first coupling capacitor 124**, **first demodulator 126**, **second coupling capacitor 134**, **second amplifier 128**, and **third amplifier 136** as illustrated in **Fig. 4** and described hereinabove.

The output of the associated **preprocessing circuit 234.2** is converted to digital form by at least one associated **first analog-to-digital converter 236.2**, and the signal therefrom input to the **processor 238**.

The **first 202** and **second 204 magnetic sensors**, as described heretofore, are adapted to each individually function in cooperation with the corresponding **left 206** and **right 208 sides** of the **vehicle 12** in accordance with any of the earlier described embodiments of magnetic sensors, for example, as identified by **magnetic sensors 10, 100, 100.1, 100.2, 100.3, 100.4, 100.5, 100.6**.

Furthermore, the **oscillation frequency f_1** of the **oscillator 210.1** associated with the **first magnetic sensor 202** is adapted to be different from the **oscillation frequency f_2** associated with the **oscillator 210.2** of the **second magnetic sensor 204**, so that the signals from the corresponding **first coils 216.1** and **216.2** can be differentiated from one another, to the extent that the **magnetic circuits 222.1, 222.2** associated with the **first coils 216.1, 216.2** associated with one **magnetic sensor 202, 204** interact with the **magnetic sensing elements 224.2, 224.1** associated with the other **magnetic sensor 204, 202**. For example, in one embodiment, the **oscillation frequency f_1** of the **oscillator 210.1** associated with the **first magnetic sensor 202** is about **10 KHz**, whereas the **oscillation frequency f_2** associated with the **oscillator 210.2** of the **second magnetic sensor 204** is about **20 KHz**. It may be beneficial for the respective **oscillation frequencies f_1** and **f_2** to be adapted so that one is not a harmonic of the other, for example, so that the **oscillation frequencies f_1** and **f_2** are relatively indivisible or irrational with respect to one another, so as to preclude the prospect of a harmonic of a signal generated by one **magnetic sensor 202, 204** being interpreted as originating from the other **magnetic sensor 204, 202**.

The **first magnetic sensor 202** further comprises an associated **third resonant circuit 240.1**, e.g. comprising a series combination of an associated **inductor 242.1** (e.g. a **third coil 242.1'**) and a **third capacitor 244.1**. The **third resonant circuit 240.1** further comprises an associated **current sensor 246.1**, for example an associated **series resistor 248.1** and an associated **second amplifier 250.1**, e.g. a differential amplifier, adapted to measure the voltage across the associated **series resistor 248.1**. The **current sensor 246.1** may be embodied in other ways, for example by measuring the voltage across either the associated **inductor 242.1** or the associated **third capacitor 244.1**, or by measuring a magnetic field generated by the current flowing in the associated **third resonant circuit 240.1**. The **third**

resonant circuit 240.1 is adapted to have a **resonant frequency** $f_{3.1}$ that is substantially equal to the **oscillation frequency** f_2 associated with the **oscillator 210.2** of the **second magnetic sensor 204**. The output of the associated **current sensor 246.1**, e.g. the output of the associated **second amplifier 250.1**, is operatively coupled to a **second analog-to-digital**
5   **converter 252.1**, and the output therefrom is operatively coupled to the **processor 238**.

Furthermore, the **second magnetic sensor 204** further comprises an associated **third resonant circuit 240.2**, e.g. comprising a series combination of an associated **inductor 242.2** (e.g. a **third coil 242.2'**) and a **third capacitor 244.2**. The **third resonant circuit 240.2** further comprises an associated **current sensor 246.2**, for example an associated **series**
10   **resistor 248.2** and an associated **second amplifier 250.2**, e.g. a differential amplifier, adapted to measure the voltage across the associated **series resistor 248.2**. The **current sensor 246.2** may be embodied in other ways, for example by measuring the voltage across either the associated **inductor 242.2** or the associated **third capacitor 244.2**, or by measuring a magnetic field generated by the current flowing in the associated **third resonant circuit**
15   **240.2**. The **third resonant circuit 240.2** is adapted to have a **resonant frequency** $f_{3.2}$ that is substantially equal to the **oscillation frequency** f_1 associated with the **oscillator 210.1** of the **first magnetic sensor 202**. The output of the associated **current sensor 246.2**, e.g. the output of the associated **second amplifier 250.2**, is operatively coupled to a **second analog-to-digital converter 252.2**, and the output therefrom is operatively coupled to the **processor**
20   **238**.

The magnetic circuit **222.1** associated with the **first coil 216.1** of the **first magnetic sensor 202** includes both **second locations 230.1** and **230.2** respectively associated with the **first 202** and **second 204 magnetic sensors** respectively. Similarly, the magnetic circuit **222.2** associated with the **first coil 216.2** of the **second magnetic sensor 204** includes both
25   **second locations 230.2** and **230.1** respectively associated with the **second 204** and **first 202 magnetic sensors** respectively. Accordingly, **magnetic flux 49**, ϕ generated by the **first coil 216.1** of the **first magnetic sensor 202** is sensed by the **magnetic sensing element 224.2** of the **second magnetic sensor 204**, and **magnetic flux 49**, ϕ generated by the **first coil 216.2** of the **second magnetic sensor 204** is sensed by the **magnetic sensing element 224.1** of the
30   **first magnetic sensor 202**. The **third resonant circuits 240.1, 240.2** are series resonant, and accordingly, have a minimum resistance at their respective **resonant frequencies** $f_{3.1}$, $f_{3.2}$, so that the frequency response of current therethrough exhibits a maximum a the respective

resonant frequencies $f_{3.1}$, $f_{3.2}$. Stated in another way, each **third resonant circuit 240.1, 240.2** acts as a current sink at its respective **resonant frequency** $f_{3.1}$, $f_{3.2}$, and a measure of current therethrough provides a measure of the magnitude of an associated frequency component of the **magnetic flux 49**, ϕ, having the corresponding **resonant frequency** $f_{3.1}$,

5   $f_{3.2}$, that is sensed by the corresponding **first coil 216.1, 216.2**. Accordingly, the current sensed by the **current sensor 246.1** associated with the **first magnetic sensor 202** provides a measure of the operativeness and operation of the **first coil 216.2** associated with the **second magnetic sensor 204**, and the current sensed by the **current sensor 246.2** associated with the **second magnetic sensor 204** provides a measure of the operativeness and operation of the

10   **first coil 216.1** associated with the **first magnetic sensor 202**, so that each **magnetic sensor 202, 204** can be used to verify the operation of the other, and thereby provide a measure for safing the other **magnetic sensor 204, 202**.

Responsive to a first measure of operativeness of the **first coil 216.1** associated with the **left side 206** of the **vehicle 12** – which first measure of operativeness is responsive a signal

15   from the **current sensor 246.2** associated with the **third resonant circuit 240.2** associated with the **second magnetic sensor 204** associated with the **right side 208** of the **vehicle 12** -- the **processor 238** provides for disabling a **first safety restraint actuator 254.1** associated with the **left side 206** of the **vehicle 12** if the first measure of operativeness indicates that the **first coil 216.1** is inoperative. Otherwise, if the **first magnetic sensor 202** is otherwise

20   operative, then the **first safety restraint actuator 254.1** associated with the **left side 206** of the **vehicle 12** is actuated responsive to a signal from the associated **magnetic sensing element 224.1** associated with the **first magnetic sensor 202** associated with the **left side 206** of the **vehicle 12**.

Responsive to a second measure of operativeness of the **first coil 216.2** associated with

25   the **right side 208** of the **vehicle 12** – which second measure of operativeness is responsive a signal from the **current sensor 246.1** associated with the **third resonant circuit 240.1** associated with the **first magnetic sensor 202** associated with the **left side 206** of the **vehicle 12** -- the **processor 238** provides for disabling a **second safety restraint actuator 254.2** associated with the **right side 208** of the **vehicle 12** if the second measure of operativeness

30   indicates that the **first coil 216.2** is inoperative. Otherwise, if the **second magnetic sensor 204** is otherwise operative, then the **second safety restraint actuator 254.2** associated with the **right side 208** of the **vehicle 12** is actuated responsive to a signal from the associated

magnetic sensing element 224.2 associated with the **second magnetic sensor 204** associated with the **right side 208** of the **vehicle 12**.

While specific embodiments have been described in detail in the foregoing detailed description and illustrated in the accompanying drawings, those with ordinary skill in the art will appreciate that various modifications and alternatives to those details could be developed in light of the overall teachings of the disclosure.

For example, it should be understood that the above described embodiments, although described separately herein, can be combined with one another as additional embodiments of the **magnetic sensor 100**. The sensitivity of the **magnetic sensor 100** to crashes, or other detectable events, can be set to a desired level by adjusting gain and/or threshold values associated therewith. Furthermore, in addition crash sensing and safing, the above described embodiments -- when incorporating a **magnetic circuit 38** involving a **door 14** – can be used to detect the state of opening (i.e. open or closed) of the **door 14**, either responsive to the self inductance of the **first coil 42**, or responsive to a **second signal 114** from an associated **magnetic sensing element 50 / second coil 54**.

Accordingly, the particular arrangements disclosed are meant to be illustrative only and not limiting as to the scope of the invention, which is to be given the full breadth of the appended claims and any and all equivalents thereof.